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# WORKSHOP

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## NEW PARADIGMS FOR MANUFACTURING

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Arlington, Virginia

May 2, 3, and 4, 1994

Edited by  
Amar Mukherjee and Jack Hilibrand

Sponsored by  
The National Science Foundation  
Computer and Information Science and Engineering Directorate  
Microelectronics Information Processing  
Systems Division

NSF participants were involved in the technical discussions in the workshop but did not participate in the recommendations. The opinions expressed in these proceedings are those of the individual participants and do not necessarily represent NSF policy. Their recommendations are currently under review by NSF.

Note: This electronic version is a reconstruction of Document NSF 94-123. There may be minor differences between this electronic version produced in November 1996 and the version printed in 1994.

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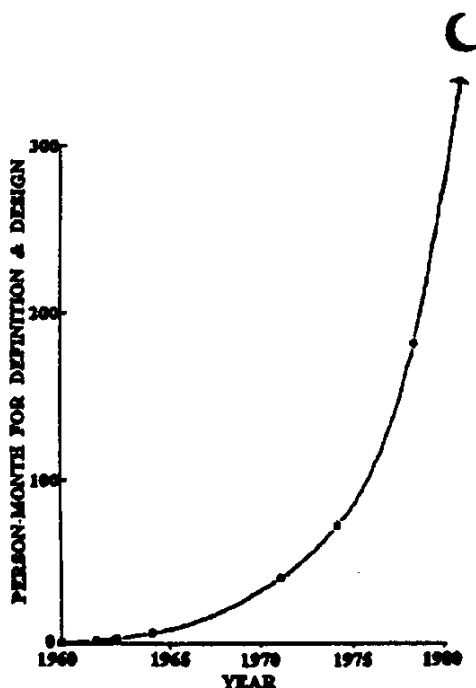
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## PREFACE

**Carver Mead**  
**California Institute of Technology**

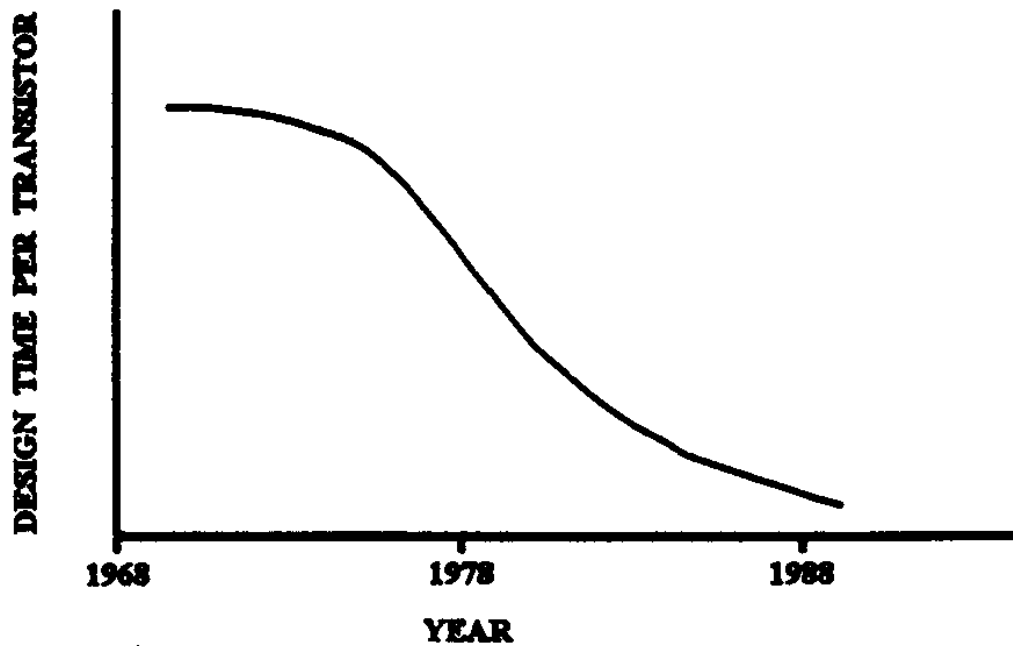
This report contains a number of references to the "VLSI Revolution", and to the role of university research, structured design methodology, the MOSIS service, new design paradigms, and tools based on those paradigms. It may be useful to review how innovation in these areas developed, and to evaluate, in the light of nearly 25 years hindsight, what has survived of these contributions. These observations will, of necessity, have a somewhat personal perspective.

The impact of the university VLSI research community on industry practice can be seen by comparing the plot of design time vs. year from a talk given by Gordon Moore in 1979 (Fig. P.1) with a similar plot shown in another Gordon Moore talk ten years later (Fig. P.2). Although some progress in the design flow would have been made following the existing industry paradigm, a great deal of the progress shown is attributable to contributions of the university VLSI community, and industrial efforts resulting directly from university VLSI design-tool work.



**Figure P.1**  
**Design Time/Integrated Circuit**

An even more compelling, albeit more qualitative case can be made by comparing the chip layouts of microprocessors of the early 1970's with those of today. Virtually all high-performance designs today use highly structured methodology, with well-defined data paths and separate control logic, as taught in the VLSI design courses starting in the mid 1970's. These designs clearly outperform random-logic designs, which were the industry norm during the period, and still persist in some gate-array designs.



**Figure P.2 - Design Time/Transistor**

To make any real progress, it was necessary to actually fabricate and test the university designs, and use them in real systems. Not because one could not simulate a design to ascertain its functionality, but because one does not learn the true nature of the material world until one confronts it. Those who merely simulated derived an abstract kind of knowledge, which diverged farther and farther from the nature of real physical systems as time went on. Simulation can only answer questions that we have thought to ask---the physical system points out all the problems we didn't even think to ask about.

Providing the university community with fast-turnaround silicon fabrication was a real challenge. Personally I was very lucky to have Bob Noyce and Gordon Moore as close personal friends, and several former students working in the fabrication areas at Intel. I could sneak Caltech experimental runs through the line with little difficulty. When other universities started offering the course, we needed a more reliable route to fabrication. ARPA funded the initial MOSIS service for research use, and soon after NSF provided support for courses taught at all universities. In order to make MOSIS work over an extended period (now 15 years), we had to choose an interface to the service that could stay current with the latest process over many generations. The initial Caltech course in 1971 used 9 micron pmos. The next process, described in the Mead-Conway book, was depletion-load nmos. Next was vanilla CMOS, followed by 2-metal CMOS, then 2-poly, 2-metal CMOS, followed by BiCMOS.

Over the entire period, the MOSIS interface has not changed, except for two simple files unique to each process. How was that possible? The choice of interface was made to coincide with the most generic definition of wafer fabrication: The final physical wafer would be built up of layers, applied one after another. Each layer had a 2-dimensional definition. The design rules could be specified by simple geometric relations among the various layers. We specified the result of the operation on the wafer rather than how the result was to be obtained, thus leaving the processing detail to the particular fabricator. We made no attempt to specify how the layers were to be used beyond the process-specific devices spelled out by the supplier (which combinations made transistors, etc.).

By now we are using a vast array of devices never contemplated when the interface was defined, nor specified by the fab supplier---high-voltage transistors, floating-gate devices, tunneling junctions, hot-electron injection structures, hall-effect devices, lateral-pinch transistors, varactors, charge-pump

devices, photo-transistors, lateral bipolar transistors, and many more. A great wave of innovation has occurred at every level of silicon design. Much of this innovation would not have occurred if we had decided a priori what primitive elements must be used (gate-level description, for example). The point here is that we cannot predict what dimensions of innovation will occur, and thus it is essential to allow as much freedom as possible in the use of whatever technology is available.

As we search for parallels between our VLSI experience and the challenge of rapid prototyping of mechanical systems, several similarities and differences suggest themselves.

### **Similarities:**

- A well-established industry clinging to an existing paradigm.
- Leverage use of existing commercial processes.
- University knowledge crucial to improvement in design methodology.
- Important to build real systems to identify real problems.
- Abstraction of process possible with moderate loss of generality.
- Computing resources and techniques can revolutionize design paradigm.

### **Differences:**

- Three-dimensional nature greatly increases complexity.
- Many more processes available (necessary ?).
- Physical injury possible, not only from product but from experiment.
- Fabrication capability much less expensive (university can own one).
- Much shorter fabrication cycle (hours vs. weeks).

The similarities suggest that something is to be learned from the VLSI experience. The differences suggest that we must be thoughtful in drawing the parallels. For example, because fabrication capability is much less expensive for many mechanical processes, it would be more sensible to encourage universities to select their own processes rather than develop a central capability as we did with MOSIS. It is certainly too early to specify which processes should be the favored ones---this selection should come as a natural result of competition among research groups. The synergy between computing techniques and mechanical design is even deeper than it is with electrical technology, and will certainly be at the heart of any breakthrough in mechanical design paradigm.

In summary, I am confident that a true revolution is possible in mechanical design using modern computing technology. Many avenues will need exploration to find the ones that truly pay off. Our universities are an ideal environment for this kind of pluralistic approach to innovation. The NSF can make a real difference in our national competitiveness, both in the near term and in the long term, by supporting research in this area.

## 0. BACKGROUND AND WORKSHOP OPERATION

The workshop was convened to examine the successful "VLSI experience", the lessons learned, and their applicability to other areas particularly electromechanical design and manufacturing.

The concept for the workshop was originated in a position paper "*New Paradigms for Manufacturing*" by Drs. Bernard Chern and Jack Hilibrand, preceding the workshop, which identified some of the key elements that enabled the VLSI revolution in design and manufacturing and raised a number of issues and questions. The paper charged the workshop to identify and understand the basic elements of the VLSI paradigm, their applicability to design and manufacturing more generally and to identify manufacturing processes and technologies for mechanical systems that might benefit from the VLSI experience. Finally, the workshop was charged to assess infrastructure requirements to support research on design and manufacturing for these processes and technologies. Position papers were then prepared by workshop attendees and circulated, also in advance of the workshop. Summaries of these position papers were delivered at the workshop with extensive interactive discussions of the papers by the attendees. A Panel session was then held on VLSI-oriented Rapid Prototyping Technologies for Mechanical Parts to bring the participants up to date on the status of the Solid Free-form Fabrication (SFF) technology. Each of the workshop participants then joined one of three breakout groups dealing with the following topics:

### **The Breakout Groups**

**Group 1: Key Elements of VLSI and Applicability to Mechanical Systems:** B.Chern, M. Cima, M. Cutkosky, D. Gajski, C. Sequin (Chairman), R. Sproull (Recorder), H. Voelcker and D. Whitney

**Group 2: VLSI-like Mechanical Systems: Design, Fabrication and Prototyping Techniques:** M. Cutkosky, K. Gabriel, G. Meieran, A. Mukherjee (Recorder), F. Prinz (Chairman) and E. Sachs

**Group 3: Candidates for VLSI-like Implementations and Infrastructure Requirements:** E. Antonsson, J. Beaman, J. Hilibrand (Recorder), R. Kahn (Chairman). P. Khosla, P. Losleben (Acting Chairman) and R. Riesenfeld

Each of these three groups met with the full workshop complement a number of times during the workshop to report progress to all of the attendees who met as a committee of the whole. This allowed for frequent discussions and provided feedback to the three breakout groups. The last day of the workshop was given to the preparation and presentation of more formal draft reports by the three groups and to discussion of plans for integration of the group reports and recommendations.

The remainder of this Proceedings consists of an Executive Summary section followed by the three breakout group reports with major findings and recommendations. The original position papers are included in the appendices, Section 3.4.

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It is hoped that this workshop will open the field for extended discussion of appropriate ways to apply the lessons of VLSI to more general areas of manufacturing and that these activities will attract talented individuals to the field.

## **Acknowledgments**

The editors of this workshop report want to thank all of the participants and to express their special appreciation to those participants who actively supported the preparation of this document, well beyond the call of duty: Erik Antonsson, Paul Losleben, Fritz Prinz, Richard Riesenfeld, Carlo Sequin, Robert Sproull, Herbert Voelcker, and Dan Whitney. In addition, we want to thank the reviewers for their many useful comments and suggestions: Lynn Conway, David Hodges, Carver Mead, Ari Requicha and Peter Will.

# 1. EXECUTIVE SUMMARY

The unprecedented growth of microelectronics industry in the U. S. over the last three decades has been called the "VLSI Revolution". During the eighties, VLSI has been the focus of intense activity among academia and industry which has led to the development of advanced semiconductor process technology, structured design methodologies, automated design tools, simulation models, and rapid prototyping techniques. The question naturally arises whether the lessons learned from the VLSI experience can benefit other kinds of design and manufacturing activities. This question also has a new significance today in view of the development of the National Information Infrastructure (NII), and the IITA (Information Infrastructure Technology and Applications) component of the HPCC (High-Performance Computing and Communications) Program. Advanced manufacturing processes and products are identified as one of the national challenge application areas. Given the importance of this challenge to extend US leadership in key strategic manufacturing technology and because of its large potential economic impact, NSF sponsored a workshop to examine the successful "VLSI experience", the lessons learned, and applicability to other areas particularly electromechanical design and manufacturing.

Assessing the lessons learned from the VLSI experience provides an opportunity to focus on other design and manufacturing areas that will be of significant impact in the quick-turnaround agile manufacturing of the future. Initially such areas can be addressed by identifying specific VLSI-like technologies, by encouraging research efforts in these technologies and by providing infrastructure support for their development and application to mechanical and electromechanical manufacturing.

## Differences in the Nature of VLSI and Mechanical System Design

The workshop provided an unique forum for discussions on the nature and characteristics of VLSI and mechanical design by experts from both fields and raised some fundamental issues regarding the intrinsic differences between VLSI and mechanical systems:

- VLSI circuits essentially perform logic operations and can be abstracted at different levels by formal systems which allows separation between system design, component design and fabrication. A set of design rules in 2-dimensional geometry provides a clean interface between design and fabrication.

However, mechanical systems transform energy and perform a richer array of operations on 3-dimensional objects involving physical parameters. Formal systems are not available now for describing the functional behavior of mechanical systems in a way that leads to effective synthesis algorithms. Can such systems be created to support some limited part of mechanical product design and manufacturing?

- A small number of simple building blocks or logic primitives can be used hierarchically to build a complex VLSI system. The behavior of a VLSI system can be accurately modeled in terms of the behavior of its constituent components and the VLSI fabrication processes are sufficiently predictable for the models to be both complete and accurate. These characteristics have led to the development of a set of powerful design tools for synthesis, analysis, simulation and verification.

However, in today's design of mechanical systems, the component elements often "share function" and behave differently in a system due to back loading which prevents hierarchical system design. Furthermore, a significant amount of design effort is expended taking into account such second order effects as fatigue, vibration, corrosion etc., and on the tolerance issues which arise under stringent performance requirements for mechanical systems. For VLSI circuits, side effects due to interference, parasitics, voltage fluctuations or heat build-up are usually considered less critical and can be substantially reduced by dealing with signals in digital form; these side effects can be traded off against performance. Can these differences be accommodated by the increasing power of modern software and hardware tools?



These issues underscore the need to carry on further research on abstracting mechanical engineering design and fabrication processes, modeling material properties and characteristics in structures and describing mechanical systems in mathematical languages so that the tools developed could then be integrated into a comprehensive design environment and manufacturing specification?

## Findings

The major findings of the workshop can be summarized as follows:

- **VLSI design is a highly specialized engineering design methodology, well adapted to the intrinsic nature of VLSI products.** The search for paradigm-shifting or technology-transfer opportunities to mechanical manufacturing exposed fundamental limitations in mechanical design (e.g. the lack of function to form formalisms). The adaptation of aspects of the VLSI experience to create new paradigms for mechanical and electromechanical design and manufacturing requires a critical examination of the basic nature of the similarities and differences between VLSI systems and candidate mechanical systems.
- **Basic research is needed to bring about new paradigms for manufacturing and the requisite increased automation** One of the principal impediments to increased automation of mechanical design and analysis is the lack of fundamental mechanical engineering knowledge and algorithms to perform the associated analysis or synthesis that will increase the automation of manufacturing.
- **Developing suitable *digital interfaces*<sup>1</sup> between the design and manufacturing activities is a powerful methodology for system specification which should be implemented for selected manufacturing technologies.** These opportunities extend to a range of fabrication processes wider than the MEMS and SFF processes mentioned below. In the case of VLSI design these interfaces take the form of a hierarchy of functional descriptions embodied in building blocks geometrically obedient to *design rules* which provide a clean separation between the design and the manufacturing processes. In the case of mechanical design and manufacturing what is lacking and needed is a digital interface convention, at an appropriate level of abstraction, which can provide for a clean separation between the design and the process descriptions based on a shared body of knowledge between the designer and the fabricator (embodied, at least in part, in a set of design rules). Additionally, the continuing digitalization (and conversion to electronic implementation) of analog functions in mechanical and electromechanical design and manufacturing might enhance the usefulness and cost effectiveness of such digital interfaces.
- **While there are no general paradigm or technology transfer opportunities across all of mechanical manufacturing, there are potentially important opportunities for synergy in restricted device and process domains.** Two of the emerging fabrication processes - SFF (Solid Free-form Fabrication) and MEMS (micro-electromechanical systems) - have significant similarities to VLSI manufacturing processes and layering technology. These processes provide a good starting point to apply VLSI systems design methodology and to develop analysis and synthesis tools for these technologies.
- **For SFF, MEMS and similar layer based processes, we need to encourage the evolution of standard process technologies that can be made available to designers.** Such capabilities for basic research and development in manufacturing will serve as test beds for evolving a comprehensive infrastructure to support mechanical, electromechanical and other kinds of fabrication processes. This will allow research in robust design tools to make rapid prototyping accessible to distributed design teams over the network for SFF, MEMS and other rapid prototyping manufacturing processes.

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<sup>1</sup> See Digital Interfaces to Fabrication, Robert F. Sproull in the position papers section of this report.

- **A comprehensive national infrastructure must be developed to support digital product definition for a variety of design and manufacturing activities.** The purpose of this infrastructure will be to provide a network of support facilities in design tools, description languages, knowledge data bases, modeling, simulation, fabrication and educational materials for manufacturing processes and products.
- **The contributions by industry, research laboratories, government and universities was a key to the success of the VLSI revolution.** Long term investment by the government and by industry, coupled with a clear replacement market set the stage for the VLSI Revolution. The time was right for an investment in infrastructure to rapidly bring about the changes needed for continued advances needed by the industry in the late '70s.

## Recommendations

The major recommendations of the workshop can be summarized as follows:

- **The search for paradigm-shifts or technology-transfer opportunities exposed fundamental limitations in mechanical design that should become research targets in the mechanical engineering community.** Investigate design methodologies and techniques to identify those that will lead to systematic methods for some selected class of mechanical designs. This work is likely to include research on the nature of mechanical design: methodology, models and languages to capture design abstractions and the development of design tools for selected design and fabrication processes. This effort is intended to build solid foundations for digital specification of mechanical design and fabrication processes. Initial development efforts should be focused on those technologies which can benefit from the VLSI experience and which are promising in their impact on manufacturing.
- **Support of basic research is required to understand selected mechanical fabrication and assembly processes so that they are controllable and predictable, and hence susceptible to complete automation.** Equally important is research to build solid foundations for digital specifications of designs and fabrication and assembly processes, so that design and fabrication and assembly data can be interchanged unambiguously. This research leads directly to practical improvements in design and the coupling of design and manufacturing. Because of the interdisciplinary character of much of the research proposed and the strong interplay of information technology and manufacturing, it will require the joint sponsorship, encouragement and support of the Computer and Information Science and Engineering (CISE) and the Engineering (ENG) Directorates of NSF.
- **Develop digital interface techniques and descriptive languages for the mechanical design methodology and product description based on economy, technical feasibility and simplicity.** The research should stress techniques for achieving device- and process-independence and for converting this data into process control information. These techniques should be applicable to the rapid prototyping technologies.
- **The SFF (Solid Free-form Fabrication) and MEMS (Micro-electromechanical Systems) design and fabrication processes should be investigated actively since these are technologies where the VLSI experience will be most relevant.** This work should include new materials and new object geometries and configurations as well as the development of integrated CAD/CAM environments for these technologies, design languages and libraries, process modeling and simulation tools and innovative architectures for new applications. Application of the VLSI design paradigms should be fostered where they make technical sense.
- **Evolve standard processes for the MEMS and SFF technologies and the definition of design tools and environments for rapid prototyping.** This effort should involve research teams from both academia and industry with interdisciplinary backgrounds in mechanical engineering, electrical engineering, computer science, mathematics and physics.

- **Create a national infrastructure for design and manufacturing of mechanical and electromechanical products.** This will create a technical community which will communicate and share design tools, fabrication processes, educational materials and technical expertise. This infrastructure development can start with selected technologies amenable to digital descriptions and test beds for service centers for MEMS and SFF fabrication technologies. The infrastructure will include languages (descriptions, in digital form, of geometry, process and behavior), shared fab resources (information, experience, hardware fabrication tools and software tools), educational resources (courses, conferences, personal ties and multimedia training materials for all of the hardware and software tools) and common challenges for artifact creation as well as common tools for evaluating achievements (bench marking and calibration tools).
- **The support picture which existed for the VLSI revolution is not the same for SFF or MEMS technology in either the strong industrial base or the compelling market demand.** Consequently investment in infrastructure is more important for rapid development of these technologies than was the case for VLSI. There is a compelling need for government support of infrastructure until a sufficient market develops to encourage industrial support.

More detailed research recommendations are to be found in the group reports and position papers as well as additional issues that remain to be assessed.

## 2. BREAKOUT GROUP REPORTS

### 2.1 GROUP 1 REPORT

#### *KEY ELEMENTS OF VLSI AND APPLICABILITY TO MECHANICAL SYSTEMS*

Group 1: Bernard Chern  
Michael Cima  
Mark Cutkosky  
Daniel Gajski  
Carlo Séquin, *Chairman*  
Robert Sproull, *Recorder*  
Herbert Voelcker  
Daniel Whitney

#### 2.1.1. Introduction

The success of the VLSI revolution, both in industry and in academic research, leads naturally to the question: What can we learn from that success, and how might it be applicable to the design and manufacturing of electromechanical systems? This report suggests some answers, and concludes with recommendations for initiatives the NSF could launch in the electromechanical arena.

When considering the transfer of ideas from VLSI to mechanical systems, it is important to identify comparable realms of design and manufacturing. VLSI designs represent a subset (and an increasingly pervasive one) of all electronic designs. The techniques that have emerged for VLSI design and fabrication are not, by and large, applicable today to some larger areas of arbitrary electronic design or to the design of finished products. Thus we should not try to look for parallels between VLSI techniques and *all* of mechanical engineering, but perhaps try to find specific mechanical design or manufacturing processes that might benefit from lessons learned from the VLSI experience.

Another important distinction to make is between methods for *design* and those for *procuring fabrication services*. The VLSI industry has benefited enormously not only from a set of design techniques and tools that enable very complex chips to be designed, but also from the separation of design and fabrication by a clean digital interface, so that designers can send to a fabrication facility a precise digital specification of what is to be built. The digital interface to fabrication has been critical to innovations in the VLSI industry, such as fab-less chip companies, and also to fostering innovative designs without changing details of expensive mission-critical wafer fabrication plants.

#### 2.1.2. VLSI Technology

VLSI technology is a subset of digital electronics that may be characterized by the following list of properties. Some elements apply to all digital electronics; asterisks indicate elements distinctive to VLSI.

- 1) The principal objective of a VLSI chip is to manipulate digital information. Hence, its dominant property is its logic function, defined using techniques such as Boolean relations and finite state machines. Additional properties, such as clock speed, logic density (e.g., gates

per unit area), power consumption, and package size can be of secondary importance compared to the accuracy of the logic implementation.

- 2) VLSI design depends largely on hierarchical decomposition of high-level descriptions into progressively lower levels and, ultimately, into a very small set of primitive elements, such as logic gates and latches. The hierarchy and modularity characteristic of VLSI designs is a result of a strong "separation of concerns" between levels of description, such as system blocks, register-transfer, switch-level, circuit level, and layout.
- 3) Many design aids are available and are becoming more powerful. They include libraries of high-level functional blocks [shift registers, simple ALUs (arithmetic logic units), register files, and the like], as well as specialized tools such as logic simulators, optimizers, automatic routers, timing verifiers, and others. Significant portions of the design process have been automated, e.g., synthesis from a high-level hardware description language (VHDL).
- 4) There are enough formal or *de facto* standards in VLSI design and fabrication to support competitive outsourcing at several levels. MOSIS is an early example of outsourcing, and MOSIS was made viable by the CIF description language [Mead 80], which specifies in detail the geometric layout of a chip. The design of application-specific integrated circuits (ASICs) today depends on higher-level descriptions of logic schematics. All of these standards are designed for computer-to-computer communication, i.e., they can be read and interpreted unambiguously by computer programs, but are often human-readable as well.
- \* 5) VLSI is linked inextricably with an inherently 2.5-D manufacturing process that produces layers of spatially inhomogeneous materials that can implement, collectively, spatial arrays of discrete, clocked switches and delay units. The process is based on the sequential use of 2-D spatial masks to control etching, deposition, ion implantation and other processes over the flat faces of silicon wafers.
- \* 6) A fairly small set of *design rules* expresses to the designer the constraints imposed by the fabrication process. These rules restrict designers in the placement and spacing of logical elements and interconnect, but such rules are becoming increasingly transparent to designers as design becomes more automated and the rules are embedded in libraries, automatic routing software, and synthesis tools.
- \* 7) The VLSI element functions and associated fabrication processes are sufficiently predictable that simulators of product function can be used by designers to anticipate the results of fabricating a design. Simulations may be carried out at varying levels of detail, ranging from analog circuit behavior, to gate-level simulation with accurate timing, to functional simulation. The complexity of most VLSI designs prohibits their simulation in sufficient detail to *guarantee* success, but in practice it is not uncommon for well-simulated digital designs to "work the first time" they are manufactured.

Two important observations:

- Although there are variants of the VLSI fabrication process, it can be viewed as a single generic manufacturing process (characterized by layered etching, deposition, ion-implantation, etc. steps), which has a very high capital cost. Thus the number of qualified silicon (VLSI) foundries in the USA is  $O(10^2)$ , rather than  $O(10^4)$ , with the latter number being a conservative estimate of the number of American mechanical "job shops."

- There is not a single, monolithic set of VLSI design rules, but rather a spectrum of rule-sets. At one end of the spectrum lies the spare Mead-Conway rule-set that relies on conservative element operating characteristics and thus insures essentially ideal digital behavior and total decoupling of circuit elements [Mead 80]. Toward the other end of the spectrum lie more refined rules and models that obtain high performance needed for state-of-the-art devices like DRAMs by using aggressive element operating characteristics, and accommodate the quasi-analog and interactive element behavior that aggressive operation engenders.

### **2.1.3. Mechanical Products, Design, and Manufacturing**

#### **2.1.3.1. Mechanical products**

Whereas VLSI devices traffic in information quantized into bits, the underlying commodity in mechanical devices is energy in many forms: kinetic, elastic, thermal, fluidic, and more. Mechanical devices generally must respect the continuum properties of energy fields, and much of their character (e.g. form) derives from constraints imposed by energy handling. Mechanical products embrace a very wide range of objects, from single-part paper clips to commercial aircraft with more than a million parts. Neither the designs, nor the design techniques, nor the fabrication methods are homogeneous.

Mechanical products are quasi-combinatorial or modular only at intermediate and higher system levels.<sup>2</sup> The crossover point for modularity seems to be at significant-part counts of  $O(10)$  –  $O(100)$ . (Washers, standard fasteners, and the like are not considered "significant.") For example, an industrial compressor or a household washing machine has  $O(100)$  significant parts that are custom designed as an aggregate and set the character of the product. Subsystems—pumps, motors, transmissions, controllers—are attached, each having  $O(10-100)$  significant parts designed as an aggregate, and each being either a custom design or, more usually, a catalog item. (There are many exceptions, because the variety of mechanical goods is enormous. Large fabricated structures such as commercial jet aircraft probably contain  $O(1000)$  significant parts or subsystems, but there are many duplicates in the set.) There are no known sets of "functional primitives" for mechanics that are in any sense analogous to the Boolean and sequential-logic primitives of digital electronics. (The low-order kinematic pairs—two-element joints with one or two relative degrees of freedom—have been studied as possible primitives, but they generally do not qualify because they cover too small a fraction of all concerns that need to be addressed in a design.)

#### **2.1.3.2. Mechanical design**

Mechanical design is significantly combinatorial in the early, top-down phases when major subsystem decisions are being made and the product configuration is being set. As design becomes more detailed and falls below the  $O(10-100)$  part-count threshold, modularity is gradually abandoned and function-sharing becomes the guiding principle. Shared-function designs are the antithesis of modular designs, and the importance of function sharing sets mechanical design apart from software design and modern electronic design (but not from old-fashioned electronic design; oldsters may recall that a single 6SN7 often served as an i-f buffer, audio detector, and audio amplifier). The case for function sharing rests on efficiency—reduced weight, lower part count, fewer assembly operations—although these advantages sometimes impose higher tooling costs.

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<sup>2</sup> By "quasi-combinatorial or modular" we mean (informally) that a system can be partitioned into subsystems, each with definable inputs, outputs, and internal transformations that relate inputs to outputs. Non-modular systems must be dealt with as a whole, rather than as an interacting set of smaller aggregates (subsystems).

The design of shared-function parts and assemblies, and mechanical goods in general, is complicated by several factors that reflect their very physical or mechanical character. For example:

- Mechanical components often carry or transform high powers or loads. In such cases catastrophic failure and safety usually are primary concerns that must be addressed directly and limit the opportunities for modularity and hierarchical design.
- Significant side effects usually accompany the primary functional behavior of mechanical components, and considerable design effort must be devoted to anticipating and mitigating these effects. For example, thermal transients, as in starting an engine or a furnace, induce mechanical strain that, if not controlled, can cause unstable vibrations, fracture, and other unpleasant effects.
- The behavior of mechanical elements changes when they are interconnected because they load one another. Their scale (size, mass, stiffness, etc.) does not permit isolation through the impedance-ratio buffering techniques that are so effective in electronics.
- Mechanical design is inherently three-dimensional. Both VLSI and mechanical design present space allocation challenges, but these are more difficult in 3-D—especially when they involve interactions amongst distributed interacting energetic regions (heat, stress, vibration, and so forth).
- Design tools for primary behavioral modeling, analysis, and simulation have been under development for several decades; they are now reasonably effective and increasingly widely used, albeit computationally expensive. Facilities for handling multi-mode behavior are rudimentary and often computationally prohibitive, but are improving (slowly).
- There are no design rules that convert functional specifications into geometric layouts. This reflects a very basic deficiency in mechanical engineering: the lack of formal methods for describing mechanical functions in a manner that leads naturally to the synthesis of mechanical structure.
- Design-rule violations or errors in the algorithms that prepare mechanical parts for fabrication can endanger fabrication equipment and personnel.

### **2.1.3.3. Manufacturing processes**

Some 200–300 distinct "unit manufacturing processes" are in active industrial use today; Figure 1 provides a taxonomy for discussing them. Some are more than 5000 years old, and until very recently none were understood in scientific terms, meaning we had no mathematical models for their operation or effects. (The current set of 200–300 processes contains "functional equivalents," in the sense that some processes can replace others if, for example, the production volume warrants the use of special tooling.)

While a lot could be said here about processes, the pertinent facts for our current mission are probably these: (1) different processes have different effects on materials, and generally do more than merely change the shape of a workpiece, and (2) probably 1/4 to 1/2 of today's 200–300 processes are necessary to effect the material transformations required by complex contemporary designs; the notion of standardizing on a small number of processes (fewer than ten, say) to make everything is simply not viable. However, there may be important subsets containing a few processes that could address a significant product space.

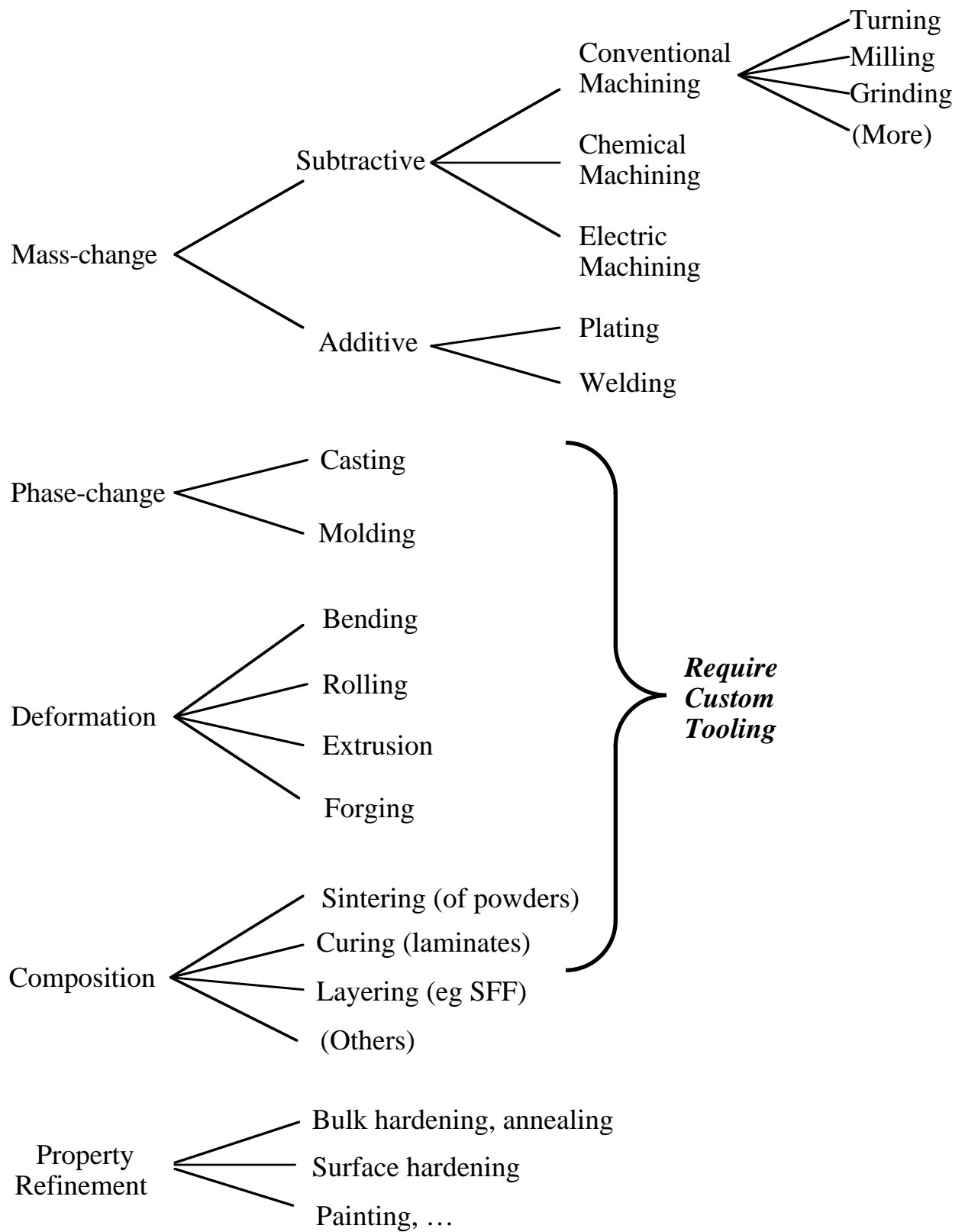


Figure 1: Manufacturing processes.



## 2.1.3.4. Practices and protocols

### *The Principle of Process Independence*

Mechanical design has been governed for the past several decades by a doctrine of strict process independence (except for parts or products made wholly in-house or by captive suppliers). In earlier times designers were allowed to specify parts via notes on drawings, such as "Drill and tap 1/4 x 20 NC", or "Rough-mill Slot C then grind Face D", but now such process-dependent statements are prohibited. The current doctrine, per Section 1.4(e) of the ANSI Y14.5 Standard on Dimensioning and Tolerancing [ANSI 82], says in effect: specify precisely the *result* you want in geometrical and material-property terms, *not* how to obtain it. Process independence has several advantages, notably –

- it facilitates outsourcing (severe procurement problems in WW-II motivated the initial adoption of the principle);
- it provides great freedom in respect to manufacturing methods, in that any set of processes can be used (at least in principle) if specifications are met;
- it makes inspection non controversial, at least in principle (see *Standards* below), and
- it finesses the difficult problem of verifying the equivalence of allegedly identical parts produced by different processes.

Process independence also carries some disadvantages or dangers. Chief amongst these are the following.

- By enabling designers to focus solely on function and ability to assemble, the process independence principle almost encourages the design of expensive and/or unmanufacturable parts and products. The remedies include training designers in the rudiments of manufacturing, assigning manufacturing experts to design teams, and so forth.
- The conversion from process-independent specifications to explicit process and tooling plans requires extensive and detailed knowledge of manufacturing processes, knowledge that only now is beginning to be codified systematically. Thus most of the conversion is still done by experienced artisans, known as *process planners*. However, research on automatic process planning is progressing, and some areas of automatic tooling design (e.g. for molds and dies) are progressing quite rapidly.<sup>3</sup>
- The validity and completeness of a process-independent design, and of inspection plans for parts made to the design, can be no better than the validity and completeness of the language in which the design is cast. The widespread introduction of computer controlled machinery (NC machines, robots, coordinate measuring machines) in the 1970s and '80s exposed some major gaps and informalities in the Y14.5 drafting standard, and associated inspection practices, that began to cause very serious problems in the later 1980s. These are now being rectified, as noted below under *Standards*.

### *Standards*

The design and manufacturing of mechanical products are governed by relatively elaborate sets of national, international, and industry-specific standards. The most important are those governing product safety, e.g. boiler and elevator codes. Part definitional standards have been set for almost 50 years by the series of Y14.5 drafting standards, which are likely to be merged in the next 1–2

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<sup>3</sup> 'Rapidly' is a relative term. Progress in mechanical domains is typically measured in decades rather than years, as in electronics.

decades with standards more attuned to CAD/CAM technology, e.g. IGES and PDES/STEP.<sup>4</sup> Manufacturing and part-inspection apparatus, and also factory communication protocols in the MAP family such as MMS<sup>5</sup>, are also covered in large measure by standards. One of the oldest is the "M-code, G-code" language for NC controllers [EIA 79], which traces its lineage to the 1950s.

In recent years interest has grown considerably in the character of the standards governing mechanical design and inspection. Notably, in 1989 a major attack was launched by the ASME Y14 and B89 standards committees (with growing assistance from the research community) on the gaps and informalities noted earlier. The results of this work will become apparent in late 1994, when a new version of the basic Y14.5 standard will appear [ASME 93a, Neumann 94], together with a new and critically important companion document, Y14.5.1 "Mathematical definition of dimensioning and tolerancing principles" [ASME 93b, Walker 94]. In 1996 a wholly new and much needed gauging standard, B89.3.2 "Dimensional measurement methods," is scheduled to appear.

By contrast, VLSI design and fabrication use fewer, conceptually simpler standards. Although proprietary and vendor-specific data formats and design libraries pose significant problems in the VLSI realm, exchanging digital design information is much simpler for VLSI than for mechanical designs.

### *Digital Interfaces to Manufacturing Processes*

Digital specifications and protocols are used in two quite distinct ways in making mechanical objects. First, many machines used in manufacturing processes are outfitted with digital controls, so that each machine can be precisely controlled using machine-specific techniques. Second, a digital specification can be used to indicate what is to be built, in a way that is independent of specific machinery or processes.

Increasingly, mechanical manufacturing processes are controlled by digital mechanisms or driven by digital data. Programmable controllers are common, numerically-controlled machining (CNC) is in widespread use with cutter paths often derived from CAD models, and the use of coordinate measuring machines and robots is spreading. While some of these devices are programmed in a free-standing mode, almost all of the newer machines now have interfaces for MAP-style networks and thus can be integrated as factory automation progresses. The delays in integration generally are *not* attributable to deficient technology, but rather to the major management challenges and dangers that integration poses.

It is worth noting that while almost all newer machines have digital interfaces which honor the pretty good communication protocols established by MMS and similar MAP-family standards, all have provisions for manual over-rides, and the over-rides are used frequently by factory-floor operators. The reason is simple: nearly all manufacturing processes still contain large elements of black art, and until we understand processes more deeply in traditional scientific terms, human intervention will continue to be essential.

Device- and process-independent digital interfaces to mechanical fabrication are not well developed. Some fabricators will accept digital models produced by popular CAD programs, perhaps converted into a vendor-independent standard such as STEP. These models concentrate on product geometry

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<sup>4</sup> IGES: Initial Graphics Exchange Standard; PDES: initially Product Data Exchange Specification, now Product Data Exchange using STEP; STEP: Standard for the Exchange of Product model data. See [Laurance 94] for a useful view of these standards, and of their conceptual roots in the graphics, CAD, and computer science database communities.

<sup>5</sup> MAP: Manufacturing Automation Protocol; MMS: Manufacturing Messaging System.

but leave other important aspects of the finished product unspecified. A human process planner uses these models and a few computerized aids to derive process-specific digital data to drive a manufacturing process, e.g. the low-level NC code of RS-274D [EIA 79]. Automatic process planning is in its infancy. By contrast, VLSI product specifications can be automatically converted into process-control data.<sup>6</sup>

## 2.1.4. Findings

### 4.1. Adaptable transferable design methodologies or disciplines

Some mechanical items can be designed with more systematic techniques and components than is generally realized. Furthermore, many modern design challenges cannot be met unless more systematic approaches are used. These challenges include:

- Reduced time to market
- Reduced design budget
- Need to design for unpredictable location of manufacturing facility
- Opportunity to reuse past designs and design heritage
- Need to make design quality standardized and accountable
- Opportunity to design families of products together in a systematic way
- Need for "custom" production at mass production speed and cost.

Some concepts from VLSI or computer science that may be applicable to these problems are listed below. Whether any *technology* can be transferred from VLSI/CS into mechanical domains is quite unclear.<sup>7</sup>

- More careful and critical methods of modularizing products during design
- Applications of database technologies to help categorize and classify low level elements that can be retrieved
- New object representations to capture geometric and non-geometric information about reusable elements (standard elements or subsets of past designs) such as "feature-based design"
- Techniques for managing complex information-intensive designs, including design logs, recording design decision dependencies, consistency maintenance (what in software engineering is sometimes known as "consistent compilation"), and integrated design tools.

Exploiting these opportunities will require innovations in design methodology, in the science, understanding, and modeling of manufacturing processes, and in computer-aided design tools.

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<sup>6</sup>There are those who argue that CIF is process-dependent, in that it depends on a layered fabrication process. While CIF indeed uses sets of two-dimensional layers to describe the desired circuit, the intent of CIF is to define the geometry of the finished product; it does not define the process steps or even the mask geometries used to achieve the product. Indeed, different integrated-circuit manufacturing processes derive quite different mask geometries from the same CIF description, and use different process sequences. In all cases, however, there are algorithms that convert the CIF specification into the forms required for a fabrication process (e.g., mask geometries) without human intervention. The design rules, however, are more process-specific. The genius of the Mead-Conway rules is that they are loose enough that many specific processes can meet them, thus allowing the designer considerable process and supplier independence. Tighter, more elaborate design rules are typically more process-specific, but are usually required to obtain high-performance products.

<sup>7</sup> It is reasonably safe to predict that VLSI/CS can provide some useful language structure (i.e. *syntax* ) for mechanical problems, but language structure without well defined and relevant domain knowledge (i.e. *semantics*) is dangerous: it can lead one to think she/he knows more about a problem than he/she really does know. Three decades of sporadic interaction between the AI and engineering communities provide plenty of examples.

#### **2.1.4.2. Immediate opportunities in mechanical fabrication processes**

Some emerging mechanical fabrication processes, by their nature, favor approaches to design and fabrication automation that are similar to those used in VLSI.

##### *Micro-electro-mechanical (MEM) devices*

The class of micro-electro-mechanical devices manufactured by VLSI-like etching and deposition processes, on dimensional scales commensurate with those used in early electronic VLSI, are credible mechanical cousins to electronic VLSI devices. They are the only close relatives we have identified to date, and they have some unusual properties from a mechanical perspective—notably that their components are fabricated and assembled essentially simultaneously, rather than sequentially. While the tools and techniques devised for VLSI design are suggestive, fabrication of micro-mechanical devices presents new problems, such as the need to model anisotropic etching processes.

##### *Solid free-form (SFF) processes*

The family of processes called Solid Free-Form (SFF) fabrication shares some of the characteristics of the generic VLSI process, notably fabrication by 2.5-D layered deposition (and conceivably etching). The fabrication process is thus pattern-insensitive, like that of VLSI. However, the dimensional scale of SFF artifacts is typically 100X larger than that of electronic VLSI artifacts, the physical principles of the underlying processes (there are several) are different from those of electronic VLSI, and SFF processes have been developed largely independently of electronic VLSI technology. Moreover, the designer requires three-dimensional modeling and other mechanical analysis tools, rather than the far simpler 2-D tools used by VLSI designers.

##### *Electro-mechanical systems*

Solid Free-Form fabrication processes offer the potential to fabricate complex integrated mechanical parts and subsystems with embedded sensors, actuators, and control electronics. However, design tools and digital interfaces to such a composite fabrication process will require new techniques.

#### **2.1.4.3. Pragmatic opportunities**

The essence of the VLSI paradigm—a suite of digital CAD tools that drive a predictable fabrication process—can be applied to carefully selected mechanical manufacturing processes. Some fabrication processes already use mostly-digital interfaces. Some of these are amenable to a device- and process-independent interface, in which the flow of information from designer to fabricator and from fabricator to designer is in a digital form, and in which the tools and processes used by both parties use this information directly. These opportunities extend to a range of fabrication processes wider than the MEM and SFF processes mentioned above.

#### **2.1.4.4. Basic research needed**

One of the principal impediments to increased automation of mechanical design and analysis is the lack of fundamental mechanical engineering knowledge and algorithms to perform the associated analysis or synthesis that will increase the automation of manufacturing.

### **2.1.5. Recommendations**

Because of the interdisciplinary character of much of the research proposed below, it will require the joint sponsorship, encouragement, and support of DMI/ENG and MIPS/CISE.

#### **2.1.5.1. Systematic design**

We recommend investigations of design methodologies and techniques that lead to more systematic methods for selected kinds of mechanical design. This work is likely to include developing design tools, perhaps specialized to narrow design domains or to narrow process domains.

#### **2.1.5.2. Emerging fabrication processes**

We recommend that the science, technology, and applications of SFF fabrication and of micro-electro-mechanical devices and fabrication processes be investigated actively. Support should be provided for items such as languages, tools, data formats, rule checkers, and usage guidelines that enable designers to exploit these processes and fabricators to produce predictable parts. Linkages to traditional VLSI design and processing technology should be fostered when they make technical sense.

It is important to support designers and design-tool construction as part of the exploration of these new processes, so that significant designs can be attempted. An important component of these tools is robust, well-defined methods for interchanging design information, including descriptions of a finished part, process plans, design rules, or combinations.

#### **2.1.5.3. Pragmatic opportunities**

We recommend supporting the refinement of digital interface techniques to selected promising mechanical fabrication processes. These processes should be selected to be:

- Able to fabricate significant classes of products economically
- Small enough in number to focus programmatic resources to have impact and demonstrate technology transfer
- Restricted to designs that avoid the kinds of strong interactions exhibited by high-performance mechanical systems (e.g., automotive transmissions that involve thermal, strength, vibration, energy conversion, fluid containment, etc.).

This research should stress techniques for increasing device- and process-independence in digital interfaces and for converting this data into process-control information.

#### **2.1.5.4. Basic research**

We recommend support of basic research required to understand selected mechanical fabrication and assembly processes so that they are controllable and predictable, and hence susceptible to complete automation. Equally important is research to build solid foundations for digital specifications of designs and fabrication and assembly processes, so that design and fabrication and assembly data can be interchanged unambiguously. This research leads directly to practical improvements in design and the coupling of design and manufacturing.

## 2.1.6. References

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## 2.2 GROUP 2 REPORT

### *VLSI-LIKE MECHANICAL SYSTEMS: DESIGN , FABRICATION AND PROTOTYPING TECHNOLOGIES*

Group 2: Mark Cutkosky  
Kenneth Gabriel  
Gene Meieran  
Amar Mukherjee, *Recorder*  
Fritz Prinz, *Chairman*  
Emanuel Sachs

In trying to adapt the “VLSI experience” to the new paradigms for manufacturing, we must recognize that some of the key elements of the VLSI paradigm are not applicable to all mechanical systems. The workshop identified two specific emerging VLSI-like layered fabrication processes - MEMS (micro-electromechanical systems) and SFF (solid free-form fabrication) - that favor approaches to design and fabrication automation that are similar to those used in VLSI. The workshop also recognized that there are certainly other promising areas that may benefit from the VLSI experience, such as laser cutting, welding and cladding, electron discharge machining, numerically controlled machining, injection molding, sheet metal forming, perhaps even casting and forging. In this report, we discuss taxonomies that relate MEMS and SFF to VLSI and identify some of the design challenges that must be addressed for future developments for these technologies. We report our major findings and conclude with recommendations for future initiatives.

#### 2.2.1. The MEMS and SFF Technologies

MEMS (Micro-ElectroMechanical Systems) denote devices or arrays of devices of millimeter dimensions that combine electrical and mechanical components that are fabricated and assembled simultaneously on silicon wafers using semiconductor process technology such as etching (isotropic and anisotropic), metalization, diffusion and implantation. Typical application domains of MEMS are sensors, actuators, pumps, valves, motors, inertial measurement units, optical and electromagnetic beam steering and biotechnology. MEMS have some unusual properties from a mechanical perspective - notably that their components are fabricated and assembled essentially simultaneously, rather than sequentially. MEMS benefits from decades of process research in VLSI. The variety of materials is mostly limited to those commonly used for VLSI manufacture and not necessarily optimal for a certain MEMS applications. However, available VLSI processes have reached a high degree of maturity. Hence, industrial quality parts with limited geometric complexity can be built on a routine basis. While the tools and techniques devised for VLSI design are suggestive, fabrication of micro-mechanical devices presents new problems, such as the need to model anisotropic etching processes.

SFF (Solid Free-form Fabrication) is a 2.5-D layered manufacturing technology in which a three dimensional structure is decomposed into thin cross-sectional slices built one cross-section on top of the other, embedded in complementary shaped sacrificial support structures. The fabrication process is thus pattern-insensitive, like that of VLSI. However, the feature sizes of SFF artifacts are typically 100X larger than that of VLSI circuits and range between hundreds of microns to tens of centimeters and the physical principles of the underlying processes ( there are several) are different from those of VLSI. SFF has rapidly gained industrial acceptance for prototyping of geometrically complex shapes. However, based on the limitations of today's SFF processes, most parts do not yet meet industrial standards regarding dimensional accuracy and material quality. SFF parts have been successfully used as 'masters' for near net shape processes such as casting and spraying. Common to all layered forming techniques is the incremental nature of the material build up process. Depositing one material layer on top of the other can be accomplished through sintering, local melting chemical

synthesis (e.g. photo polymerization), incremental powder binding, or otherwise gluing, brazing and soldering. The issues associated with each of these processes can be summarized as follows.

- Local melting requires significant energy input to the partially completed part which may result in the buildup of internal stress and consequently distortions.
- Sintering requires less energy to establish bonding of added layers but local voids will be left unless external forces are applied.
- Photo polymerization such as UV curing, one of the most popular techniques in today's SFF techniques, yields parts with limited mechanical properties.
- Incremental powder binding delivers green compacts with densities comparable to that achieved in powder pouring. Subsequent sintering of green compacts is often accompanied by shrinkage and distortion.
- Gluing brazing and soldering have the disadvantage of adding bonding materials to the part which are not necessarily desirable for its function or performance. Some of these difficulties can be overcome by adopting additional post processing steps between layers or after part completion. Such steps may include annealing, shot peening material infusion, and hot isostatic pressing.

In the past little interaction existed between the MEMS and SFF research community. While the basic idea to incrementally deposit and shape material layers is common to both technologies the details of the processes explored to date are significantly different. Common issues exist regarding the quality of bonding between similar and dissimilar materials, the occurrence of internal stresses due to the temperature dependence of the CTE and the difference in the CTE between adjacent dissimilar material layers. CAD issues in MEMS and SFF appear to have certain similarities. Both in terms of incrementally synthesizing material layers, designing sacrificial support structures as well as the underlying analysis tools required to predict the temperature and stress history of SFF and MEMS parts during fabrication. From a design perspective the incorporation of MEMS components into SFF parts might generate attractive and novel designs. Other differences between MEMS and SFF exist in terms of the characterization of mechanical properties (such as anisotropy for MEMS or functionally graded materials for SFF), electromechanical models and analysis tools for device functionality, synthesis procedures etc. are areas where the existing tools and techniques for VLSI do not directly apply. Perhaps the most critical difference, from the standpoint of formalizing and automating design is the interaction between design and fabrication. As yet no "clean" separation between design and manufacture exists, even in the two restricted domains of MEMS and SFF. The key point of distinction arises because of the notion of a 'system' approach in VLSI where a complex system is decomposed in terms of an aggregate of simple geometrical objects, whereas in SFF/MEMS technology, researchers (at present) think in terms of complex geometry, not in terms of complex systems. We therefore submit the following as a **vision statement** for the future SFF and MEMS technology:

*We believe that SFF/MEMS technologies are enabling technologies to conceive of, design and produce products that represent new parts and systems with complex geometry, graded material properties and combinations of disparate elements. Design and processing improvements will increase part quality and functionality, reduce costs, and permit greater quantities of parts to be fabricated with shorter turn-around times.*

### 2.2.2. Attributes of VLSI, MEMS and SFF

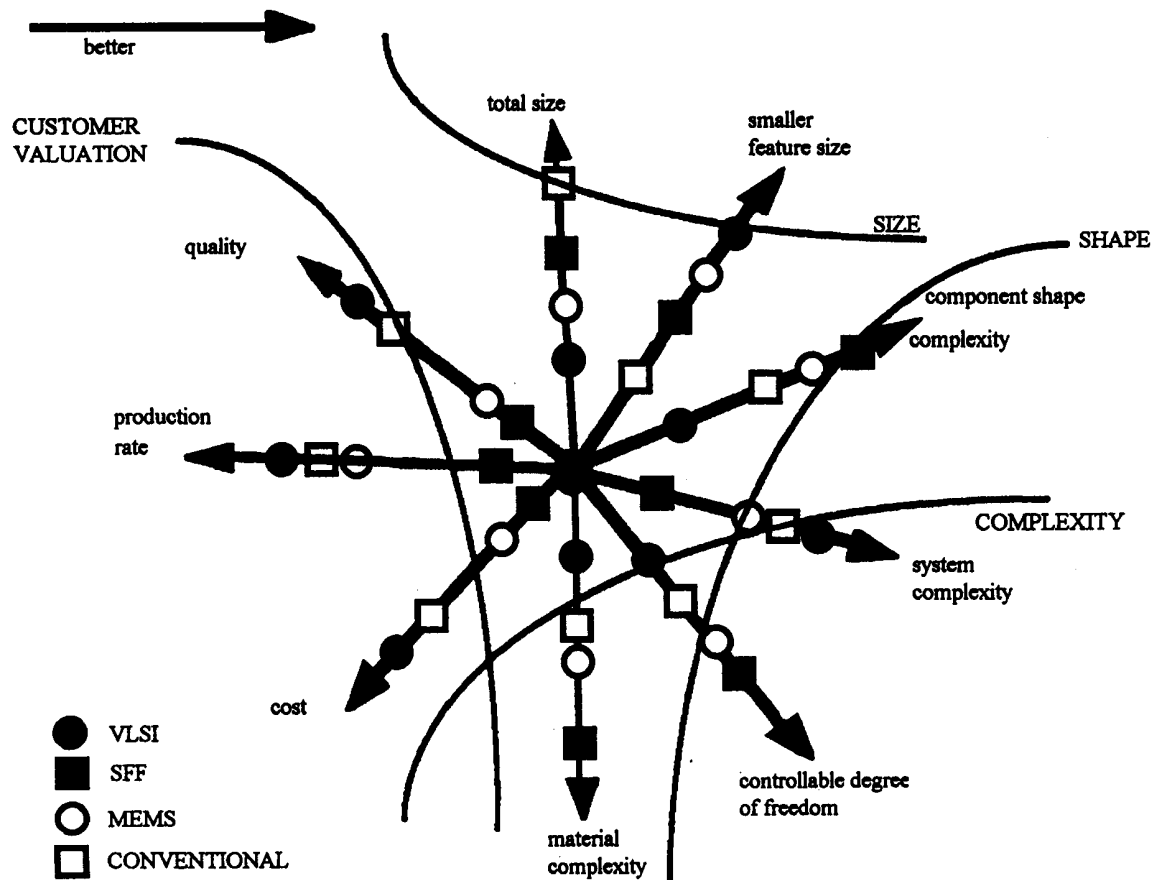
In order to better understand the design parameters that relate VLSI to SFF/MEMS, we devised a 'spider diagram' (Fig. 2.2.1) to illustrate how VLSI, SFF and conventional rapid prototyping manufacturing processes such as CNC machining compare to VLSI fabrication in terms of their ability to provide desirable characteristics. The radial arrows indicate the direction of superiority, i.e., the direction in which technology should progress. As an example, conventional manufacturing processes can produce the largest (total size) artifacts but have limitations regarding the smallest feature sizes (100 micron) and the complexity of the component shape. Informal definitions of the terms used in this diagram are as follows:

- Material complexity concerns the ability to create materials with special physical, electrical, magnetic and optical properties (e.g. microstructure control).



- Controllable degrees of freedom concerns the number of parameters (geometry, material properties etc.) that can be independently varied throughout a component or assembly. Thus, SFF processes have more degrees of freedom than machining from a single piece of metal because they can not only create complex microstructures but can continuously vary their properties.
- Component shape complexity concerns the ability to specify arbitrary geometry.
- System complexity refers to the ability to specify arbitrary functionality from a combination of many basic elements.

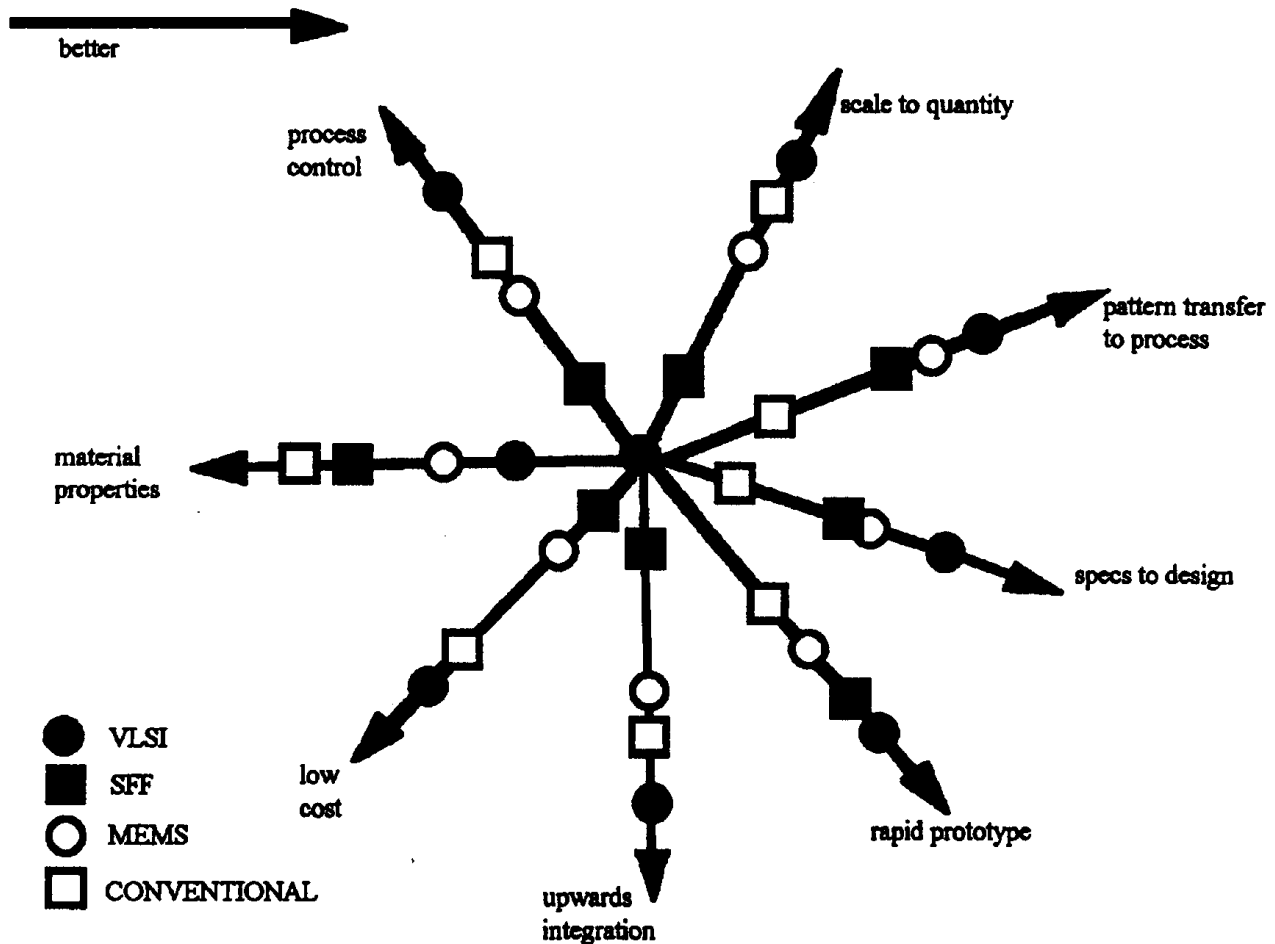
The terms cost, rate of performance and quality of the products have the usual meanings.



**Figure 2.2.1 - Domains of Value**

One key observation that can be made from this diagram is that for a number of these attributes, including system complexity, cost, part quality and production rate, VLSI fabrication is the leader, which suggests that there is something to be learned from the VLSI experience. This point is further illustrated in Fig. 2.2.2 which shows how past progress in one fabrication technology might inspire advances in another. As an example, consider the level of upwards integration in which complex functions are captured through the combination of simple elements, which traditionally has been high in the VLSI domain. In comparison, the material properties such as strength, fatigue resistance and

toughness have been highest in conventionally processed components (e.g., forged turbine blades) and are of less concern in VLSI and SFF structures. Pattern transfer to process describes the extent to which the information about the product can be contained in a mask or a set of masks and the extent to which the manufacturing process can be decomposed into a series of steps with dependence only from one step to the next. Specs to design concerns the ability to describe the functional specification of the product at higher levels of abstraction. Rapid prototyping concerns the ability to apply synthesis tools to obtain an experimental or simulated implementation of the system quickly. Scale to quantity refers to the ability to handle high-volume production once a prototype has been designed. The other parameters such as cost, process control and range of materials have their traditional meanings.



**Figure 2.2.2 - Value of VLSI Technology Transfer**

We conclude this section with a table that shows where VLSI technological capabilities may be applied to other manufacturing domains. In particular, the specific areas of VLSI that have contributed to the success of VLSI manufacturing have been mapped onto other manufacturing technologies, such as SFF and MEMS. This will show by a YES, NO or MAYBE designation whether or not a particular attribute is beneficial to that particular manufacturing capability. For example, Upward Scaling for Volume is an attribute whereby VLSI manufacturers can both use the masking technology to change product mix within a process capability and use the fact that many chips can be processed in parallel on a single wafer, to rapidly increase volume manufacturing. This capability is equally applicable to MEMS, SFF and modular design, but will not prove particularly attractive for NC machining. On the other hand, it may be attractive to use standard objects (standard cells, in case of VLSI) in MEMS and SFF, but this concept needs to be demonstrated in the future.

## Applicability of traits from VLSI Technology

Attribute	MEMS	SFF	Modular design	CNC machining
upwards scaling for volume	Y	Y	Y	N
CAD representation	Y	Y	Y	Y
process control methods	Y	Y	M	Y
rapid prototyping	Y	Y	M	Y
specifications-to-design	Y	Y	N	Y
design-to-process	Y	Y	Y	Y
dimensional control	Y	Y	M	Y
detailed material characterization	Y	Y	N	N
close ties to equipment vendors	M	Y	N	N
standardization	M	M	Y	Y

### 2.2.3. SFF and MEMS Needs

In order to achieve the potential of these two emerging technologies better engineering design languages and tools and fabrication process control are needed.

#### 2.2.3.1. MEMS

From a mechanical design perspective, MEM devices cannot be regarded simply as very small versions of standard mechanical devices. Some familiar scaling laws, e.g. for friction fail. Thus MEM devices usually cannot be designed simply by scaling established techniques for designing gears, shafts, and so forth. There is research needed on the properties of interacting materials when "large number" assumptions are no longer valid. Better simulations of three-dimensional anisotropic etching are needed, as well as better automated analysis of stress, strain, and electrical charge. Material properties including fatigue, fracture, stress concentration, friction, and wear are also required. At present, MEMS design is almost entirely ad-hoc: A designer conceives of a MEMS function, then (informally) creates a mask that the designer believes will etch into a shape that will exhibit the desired function. The designer will then create the mask, etch the shape, and test the prototype's function. This process results in many iterations, and many prototypes. Thus the present process is: mask to shape to function, the desired process is the reverse: function to shape to mask. It is for this reason that the highly formalized and automated design methods used in VLSI are potentially so valuable to MEMS design.

The key new element is that MEMS typically have to be viewed as truly three-dimensional structures, and a 2D language such as CIF (Caltech Interchange Format) is simply inadequate to describe the desired product, even though it may suffice to describe the various mask levels to make a particular structure. A solid modeling language with a user-friendly interface is needed for visualization and for simulation of the operation of the 3D structures. The language should be rather broad and generic so that it can be used to address similar issues in the context of SFF devices as well. Another new element that appears in MEMS to some degree and more strongly with SFF, is the specification of layer and position-dependent user-defined materials properties. This also needs to be captured in the specification language.

Another research issue that needs to be discussed is the question of developing standard MEMS fabrication processes and the corresponding set of design rules. At present, there are a few such ongoing efforts such as the MUMP (Multi-User MEMS Process) program offered by MCNC and the services offered for designing biomedical MEMS by the Center for Integrated Sensors and Circuits of

the University of Michigan, both supported by ARPA. In view of the rapidly evolving fabrication processes and design tools for MEMS, definition of such standard processes will have to wait a few more years. We must acknowledge that MOSIS-style rapid prototyping for VLSI has not had much direct impact on the commercial world. The design constraints imposed by the MEMS are even more limiting than those imposed by MOSIS for VLSI. The major contribution of MOSIS rapid prototyping facility was the creation of a community of researchers and designers for VLSI who acquired the knowledge of structured design methodology and successfully applied this knowledge to commercial products development. Similarly, rapid prototyping of mechanical structures would be very beneficial for educational and research purposes, but is unlikely to have much direct impact on the economy.

There is also the need to develop new packaging technologies for MEMS which, unlike VLSI, can not always be encapsulated in hermetic packages and are exposed to natural environments. MEMS devices must have their performance tested over a wide range of operating temperature, pressure, accelerations, flow rates, atmospheres, and other environments.

#### **2.2.3.2. SFF**

The processes need to be made faster and capable of smaller feature sizes (greater spatial resolution), better surface finishes, and tighter dimensional control. Better control of thermal gradients and attendant internal stresses, as parts are built up, layer by layer. Widespread implementation of SFF processes will depend on reliable specifications of the expected ranges and tolerances associated with geometric parameters and materials properties. Analysis tools must have the capability to specify, visualize and analyze continuous variations in microstructure as well as geometry. The ability to fabricate integrated assemblies or systems of dissimilar elements imposes special requirements for analyzing product performance, including variations in friction, fatigue, clearance, support, and fluid flow properties.

As with MEMS, the design description language presently used in SFF (STL) is inadequate. A new language and/or representation will greatly benefit SFF.

#### **2.2.4. Findings and Recommendations**

We conclude this report by summarizing our main findings and recommendations. We present these results in the form of bulletized items for the sake of brevity.

##### **Findings**

- No equivalent to the highly formalized and automated design methodologies that are routinely used in VLSI exist in other design domains.
- Much of the spectacular progress in VLSI devices and products (especially with regard to complexity, cost, time-to-market, etc.) can be attributed to the systematized design processes used in VLSI design.
- Two mechanical technologies that this workshop identified as especially likely to benefit from VLSI design approaches are MEMS and SFF. These two processes remove traditional fabrication constraints and open the door for entirely new classes of products with unique structures and properties.
- MEMS/SFF processes can be utilized both to manufacture products and to create tooling for specific products.
- SFF and MEMS appear to be technology areas that can benefit from understanding and applying some of the concepts and methodology used in VLSI manufacturing. Like VLSI circuits, they are created as layered structures using mask technology. In addition,
  - they have potentially wide areas of application;
  - they fill a dimensional and functionality gap;

- they represent a nodal point located between the worlds of conventional manufacturing and VLSI manufacturing
- Two basic approaches should be pursued for effective design of products and utilization of MEMS/SFF capabilities:
  - Limit the range of processing parameters and develop appropriate design rules
  - Utilize concurrent design, simulation and process planning
- There are other areas which may benefit as well from these kinds of concepts:
  - numerical control of machines that turn a product design into a finished product,
  - modular assembly of standard parts into a wide range of custom designed products (e.g., dashboard gages).
- An equivalent plan should be developed to evaluate the role of VLSI methodology in improving the performance of these processes, as well.

## **Recommendations**

### **Design**

- Initiate, develop, encourage, and support research into formal (systematized) design methods for technologies outside of VLSI, particularly mechanical technologies, including CAD/CAM framework for MEMS and SFF.
- Develop formal design languages for these technologies, including languages to describe the desired function; the designed artifact, and the fabrication methods.
- Develop libraries and search capabilities of commonly used design (or functional) primitives, while permitting innovative design when these primitives are not appropriate.
- Explore the development of (conservative) design rules for these technologies. This will first require that it can be shown that a beneficial trade-off exists by creating somewhat sub-optimal designs through an automated process, e.g., the savings in design time and effort offsets any reduction in performance of the design.
- Create new CAD tools for designing integrated assemblies and products with functionally graded materials (FGMs).
- Develop quality and performance measures for these technologies.

### **Process**

- Development of modeling, visualization, analysis and characterization methodologies for SFF/MEMS processes, properties and materials, such as FGMs.
- Improvements in basic process capabilities such as geometric repeatability, process control, surface finish, material hardness and density.
- Development of other material synthesis processes (e.g., laser-based processes)
- Development of quality and performance metrics and predictions for properties obtained via SFF/MEMS.
- Creation of networked, distributed SFF and MEMS service centers.
- Development of process and product representation languages, beginning with a simple, neutral, public data format.

### **Education**

- Develop appropriate courses to teach fundamentals of MEMS and SFF design and process technologies to build communities of experienced users.

### **2.2.5. Conclusions**

The experiences and techniques in developing formal methods for VLSI design are worth studying, building upon, and perhaps selectively emulating in selected, narrow mechanical technologies including MEMS and SFF.

### **References**

- [Mead 1980] Mead, C. and Conway, L., Introduction to VLSI Systems, Addison-Wesley, Reading, MA, 1980.
- [Ulrich 1988] Ulrich, K. T., "Computation and Pre-Parametric Design", TR 1043, MIT Artificial Intelligence Laboratory, Cambridge, MA, September, 1988.

## 2.3 GROUP 3 REPORT

### *CANDIDATES FOR VLSI-LIKE IMPLEMENTATIONS AND INFRASTRUCTURE REQUIREMENTS*

Group 3: Erik Antonsson  
Joseph Beaman  
Jack Hilibrand, *Recorder*  
Robert Kahn, *Chairman*  
Pradeep Khosla  
Paul Losleben, *Acting Chairman*  
Richard Riesenfeld

#### 2.3.1. Candidates for VLSI Implementation

The VLSI-like mechanical technologies identified by Groups 1 and 2 were the SFF (Solid Freeform Fabrication -- layering techniques including selective laser sintering, ink jet printing, selective area deposition, etc.) and the MEMS (MicroElectroMechanical Systems) approaches. These are the best candidates at present, though other technologies should be explored and could be added to this list. In VLSI technology, industrial manufacturing was already fairly mature when research infrastructure was put in place with great resulting benefit to related areas of research which applied VLSI technology. Although SFF and MEMS are now in the early development stage, rather than in manufacturing, the dynamics of these emerging industries are quite different than that of the semiconductor industry. The question to be addressed here is whether there is opportunity to effectively enhance the growth of these technologies by creating a supportive infrastructure.

#### 2.3.2. What is Infrastructure?

Infrastructure consists technology sharing that enables research and development efforts to move forward more rapidly and at a lower overall cost than would otherwise occur. In VLSI, we learned that there are three main components of an effective infrastructure:

- Access to the technology (tech access)
- Tools that empower the users (tools)
- Developing human resources in the user community (people).

All three of these were necessary for the rapid migration of this technology across the research and education community. Access to the technology was made affordable through the MOSIS service and because a common, simple interface with the technology providers (the industry) was defined. A great explosion of software tool development occurred at the beginning of the VLSI era and rapidly propagated through the community. The time was right for this development, not only because the industry had stalled in a design complexity crisis, but also because personal workstations also became affordable at that time. Finally, the widespread crossover of the technology into the education programs of most universities provided an important source of skilled personnel to staff the research program.

Infrastructure should encompass all of those useful and necessary elements for the technology being supported. The infrastructure elements should be sharable and available to the community when and where needed. Access to infrastructure should be affordable and easy to achieve. The infrastructure elements should be reliable and robust. Where possible the infrastructure elements should be embodied (codified) in commonly used digitally based standards for data formatting and manipulation. In the creation of a technological infrastructure certain things need to be taken for granted. In Group 3, recognizing that digital linkages are critical for our concerns, we took for granted that, in the

community, computers and peripherals are widely available, that many things are networked and that everything has a digital interface.

The objective of infrastructure building is to build a healthy research and development community capable of supporting the larger design and manufacturing activities that will grow up in the field. Infrastructure can also provide focus for a field and an agenda for moving ahead, especially if the resource managers are able to focus on their programs without excessive distraction. Infrastructure involves sharing of resources, experiences and tools. Artifact creation and artifact sharing are also valuable for community building particularly when the artifact is not achievable with any other technology. An "arbitrated self-help system"<sup>8</sup> for identifying sources of knowledge and resources can be very useful in knitting together the individual members of a community. Infrastructure can provide stability and momentum as well as encouragement for the transfer of technology within the community. A good infrastructure attracts capable people to work in a field because it provides the ability to do state-of-the-art design and development using infrastructure resources.

### **2.3.3. Historical Perspective**

Before speculating on the application of these same ideas to new technologies, it is useful to briefly review the events leading up to the VLSI Revolution. Nearly a century of research and development in semiconductors preceded the VLSI era with almost all technological innovations occurring in the industry (often with heavy government support). Much of the motivation for the invention of the transistor and subsequently the integrated circuit came from the increasing value of electronics made obvious in World War II. The government was the most important "early adopter" of new devices and the major customer of the semiconductor industry until the '70s. In addition, there was clear need to replace existing technology (vacuum tubes) for many reasons. This produced a *de facto* national infrastructure which thrived in the industrial laboratories.

This changed in the '70s. While government investment continued in key areas, the government ceased to be the major customer and the economics of the commodity semiconductor market forced a narrower focus on products which could be manufactured in volume. Beginning in the mid '60s and continuing through the '70s, government investment laid much of the groundwork for acquisition of custom and semicustom components from an industry which was increasingly disinterested in small quantity production. The late '70s resulted in a "design crisis" where it became increasingly difficult to find high volume markets which could support the cost of design. The "time was right" for a change in how VLSI chips were designed and the technologies were largely in place to bring about that change. The infrastructure that was put in place greatly accelerated that change.

### **2.3.4. Comparison to SFF and MEMS**

The historical background for these two technologies is quite different. There is neither the same long period of industrial development nor the same market demand to replace an existing technology. The same industrial research base is not likely to occur in today's economic climate (in fact it has largely disappeared for semiconductors). In the absence of these factors, it is likely that the development of infrastructure is necessary to successfully build and support the design and manufacturing communities in these mechanical fabrication fields. The elements of infrastructure can be focused to support these new processes and the technical communities that are developing them. Building these communities is as important as building the technological infrastructure for each technology since the latter alone is not sufficient for a successful manufacturing industry. Sharing of languages and test structures can significantly enhance communication within the electromechanical design and manufacturing technical community but today's communication tools (e-mail, for example) and today's languages and descriptions (drafting standards) are not adequate to the task. Exchanging data is so difficult that it is a limitation, today, on the ability of geographically separated groups to work together. This is also true for the exchange and distribution of software tools. An effective infrastructure can resolve these problems and permit a substantial speedup of technological progress.

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<sup>8</sup> Paul Losleben (Stanford University) is defining such a system for identifying and accessing key individuals.



It was noted that there is little of the sense of community in the mechanical technologies that is found in the VLSI community. Development and enhancement of a sense of community can be an important by-product of putting a sound infrastructure in place, as was demonstrated in the VLSI experience.

Although there is an annual conference on Solid Freeform Fabrication sponsored by ONR, it has not resulted in creation of the sort of communication ties that exist in VLSI community. The latest results in SFF and MEMS are not presented in professional forums and published in professional journals as quickly as is the case for VLSI. Similarly there is need for short courses that will spread the word on technological capabilities. The informal communication network is the most valuable channel for the technical community. The early NSF VLSI Design Workshops were cited as especially valuable since “there was lots of time spent milling about in the hallway” discussing design research ideas with one’s peers. Software tools are not shared in the SFF community, though there is some sharing in the MEMS community. In neither case is there a community agenda: there are lots of different ideas about finding meaningful artifacts to build and important products to target. There is recognition that getting industry partners involved can create a product line and build a community of users for these technologies. The ideal application is one that cannot be accomplished using an alternate technology.

### **2.3.5. Findings**

1. Long term investment by the government and by industry, coupled with a clear replacement market set the stage for the VLSI Revolution. The time was right for an investment in infrastructure to rapidly bring about the changes needed for continued advances needed by the industry in the late '70s.
2. The situation is not the same for SFF or MEMS technology in either the strong industrial base or the compelling market demand. Consequently investment in infrastructure is more important for rapid development of these technologies than was the case for VLSI. There is a more compelling need for government support of infrastructure until a sufficient market develops to encourage industrial support.
3. Many of the lessons learned in the development of infrastructure for VLSI also apply to these technologies. These include development of standards for sharing of data, application of computing to design, shared access to expensive fabrication facilities, coupling of research to education, and community-building activities.
4. It seems clear that the same simple interface between designer and fabricator that was available for VLSI does not exist for either of these technologies. The development of this interface is essential to shared facilities (and to some extent for shared tools) and is an important missing component of the infrastructure that would benefit these communities.

### **2.3.6. Recommendations**

Specific recommendations were made for the development of an infrastructure to support the SFF and MEMS technologies. Some of these infrastructure elements are specific to the SFF/MEMS technologies while other elements are more generally applicable to building technological infrastructures. The elements whose implementations are specific to SFF/MEMS are marked by an asterisk (\*). Those of general applicability are unmarked. Some infrastructure elements have parts that are specific to SFF/MEMS as well as parts more generally applicable and those are marked with a caret (^). They are also classified by infrastructure component addressed (tech access, tools, people)

- \*1. Support development of a digital 3-D shape and composition description language - specification of results.(tools)
- \*2. Support development of a machine-processable, digital process oriented implementation specification.(tools)
3. Provide for a common mechanism for community storage and retrieval - libraries of hardware and software building blocks.(tools, people)

4. Define common agreements on naming, ownership, abstracting, etc.(people)
- ^5. Provide shared access to fabrication for education and research.(tech access)
- ^6. Develop a community-wide policy on rights.(tech access, people)
7. Develop mechanisms and policies for sharing software design tools<sup>9</sup>.(tools, people)
- ^8. Support development of network-accessible multimedia courses.(people)
9. Provide for network based design interaction.(tools, people)
- \*10. Target at least one or two specific design-and-build objectives.(tech access)
- \*11. Provide for development of structures for bench marking, calibration and instruction.(tools)

The infrastructure elements listed above are described in abstract form so that their concrete implementations can be specified by the technological community to best meet their needs.

### 2.3.7. Infrastructure Issues

One key infrastructure issue relates to the use of a subsidized broker to provide access to services and tools (as MOSIS was used in VLSI). Clearly the establishment of a central broker, through whom the technology can be accessed effectively, benefits those just entering the field. Therefore such an infrastructure element is likely to result in early definition and use of new technology. A central broker also has a strong stabilizing influence on the community of users and suppliers by virtue of the need for development and use of standard interfaces. In addition, there can be an economy of scale with a single central broker. However, a subsidized broker can unintentionally prevent the formation of a community of suppliers each with his own effective interface capabilities. A broker can also unintentionally monopolize the communications channels and prevent the development of a healthy dialogue between the community of suppliers and the user community. Finally, an effective broker becomes a fixture in the field and it is difficult to terminate his services even when the technology has matured and there is the opportunity to build an industrial base with commercial sources competing to perform rapid prototyping and small lot demand manufacturing. In general, those who seek to become technology and manufacturing sources for the community would prefer to access their customers directly and to develop interfaces that meet the customer's needs most effectively. However, Group 3 concluded that, weighing all the pros and cons, a brokered approach to making the technology available was desirable and should be implemented.

Infrastructure inherently provides long term support for a field; it is hard to put in place and hard to dismantle once in place. This calls for commitment to long term funding, which is difficult when the money is appropriated one year at a time. The normal turnover of program management in government also makes it difficult to sustain a thrust over an extended period. The specific nature of many infrastructure elements (see 2.3.4 above) makes it difficult to transfer them to another newer technology when that might be appropriate. Finally, there is a tendency for those in command of the infrastructure to try to control the directions in which the technology and its implementations evolve. It is desirable to have multiagency funding of technological infrastructure with long term, but predictable, tail-off of the funding profile (subject to continued and substantive technological change in the field).

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<sup>9</sup> A full spectrum of software design tools will permit mechanical design at high, intermediate or low levels and provide for analysis, simulation, assembly, logical composition, rendering and testing.

### 3. APPENDICES

#### 3.1. WORKSHOP ATTENDEES

<b>Name</b>	<b>Affiliation</b>
<b>Participants</b>	
Erik Antonsson	Calif Institute of Technology
Joseph Beaman	Univ of Texas, Austin
Bernard Chern	National Science Foundation
Michael J. Cima	Mass Institute of Technology
Mark Cutkosky	Stanford University
Daniel Gajski	Univ of California, Irvine
Jack Hilibrand	National Science Foundation
Robert Kahn	CNRI
Paul Losleben	Stanford University
Gene Meieran	Intel Corp
Amar Mukherjee	Univ of Central Florida
Fritz Prinz	Carnegie Mellon Univ
Richard F. Reisenfeld	Univ of Utah
Emanuel Sachs	Mass Institute of Technology
Carlo Sequin	Univ of California, Berkeley
Daniel Siewiorek	Carnegie Mellon Univ
Robert F. Sproull	SUN Microsystems Labs
Herbert Voelcker	Cornell Univ
Daniel Whitney	Mass Institute of Technology
<b>ARPA Observers</b>	
Kenneth Gabriel	ARPA/ESTO
Lance Glasser	ARPA
Randy Katz	ARPA/CSTO
Pradeep Khosla	ARPA/SSTO

### 3.2 . WORKSHOP AGENDA

#### WORKSHOP ON NEW PARADIGMS FOR MANUFACTURING

AGENDA Monday, May 2, 1994

Time	Activity	Responsible
8:00 AM	Coffee and Fruit	
8:20 AM	Charge to the Workshop	Bernie Chern
8:30 AM	Position Papers - Presentations by Participants (12 minutes with Q&A, 2 Vu graphs max.): Sequin; Sproull; Prinz; Cima/Sachs; Cutkosky; Riesenfeld; Beaman; Siewiorek	Dan Siewiorek, Chair
10:10 AM	Coffee Break	
10:20 AM	Position Papers (cont'd): Whitney; Antonsson; Voelcker; Mukherjee; Meieran; Losleben; Hilibrand	Rich Riesenfeld, Chair
11:45 AM	Rapporteurs - Summary of Key Points (Sproull, Kahn, Antonsson)	Mark Cutkosky, Chair
12:45 PM	Working Luncheon - Discuss Issues	Mark Cutkosky, Chair
2:00 PM	Panel on VLSI-Oriented Rapid Prototyping Technologies for Mechanical Products (Michael Cima, Fritz Prinz, Joe Beaman)	Carlo Sequin, Chair
3:00 PM	Group Discussion of Panel Presentations	Carlo Sequin, Chair
4:00 PM	Break	
4:15 PM	Discussion of Key Points and Formation of Three Breakout Groups. (Selection of group chairmen and members, charter and reporting format*)	Bob Sproull, Chair
6:15 PM	Dinner - Breakout Groups Together with Group Chairmen	

\* format: group title, identification of issues, findings, research and infrastructure needs, recommendations

## **WORKSHOP ON NEW PARADIGMS FOR MANUFACTURING**

AGENDA    Tuesday, May 3, 1994

Time	Activity	Responsible
8:00 AM	Coffee and Fruit	
8:30 AM	Breakout Session - Group Agendas and Issues	Group Chairmen
12:00 PM	Working Luncheon - Brief Reports by Group Chairmen on Breakout Group Sessions	Joe Beaman, Chair
1:30 PM	General Discussion: Where do the Groups Go from Here?	Bob Kahn, Chair
2:30 PM	Breakout Session - Issues, Problems, Preliminary Recommendations	Group Chairmen
5:30 PM	General Discussion - Outlines of Breakout Session Reports to the Workshop by Group Chairmen	Fritz Prinz, Chair
6:30 PM	Breakout Groups meet at dinner; go beyond if necessary to complete preliminary reports	Group Chairmen

## **WORKSHOP ON NEW PARADIGMS FOR MANUFACTURING**

AGENDA    Wednesday, May 4, 1994

8:00 AM    Coffee and Fruit

8:30 AM    General Session - Review of Draft Reports; What else needs to be done?    Dan Whitney,  
Chair

9:30 AM    Breakout Groups - Finalization of Reports:    Group Chairmen  
Findings and Recommendations

12:30 PM    Working Luncheon - Discussion of Reports and    Herb Voelcker,  
Recommendations presented by Group Chairmen    Chair

1:30 PM    General Discussion: Integration of Workshop    Herb Voelcker,  
Findings, Recommendations to NSF and Research    Chair  
Community

3:00 PM    Workshop adjourns

### 3.3 “NEW PARADIGMS FOR MANUFACTURING”

**Jack Hilibrand and Bernie Chern**  
**April 14, 1994**

#### Introduction

This workshop is intended to examine what can be learned from VLSI development and manufacturing that will benefit other manufacturing activities.

#### Background

The development of microelectronics and its growth to a major industry in the U.S. over the past three decades can be summed up as “the VLSI experience.” It has been a very positive experience. VLSI activity is the focus of a complex interaction among design, manufacturing and venture funding in a strong market growth environment. One naturally asks: Are there other industries with the potential to benefit from the VLSI example and what research is needed to support the design and manufacture of their products? The broad scope of VLSI's nature and history can be found in the Appendices; key aspects are introduced briefly below as needed.

#### Workshop Objective

The fundamental questions this workshop addresses are:

- (a) What can we learn from “the VLSI experience” about the key elements that were essential to its success? What are these key elements and what role does each element play in enabling the VLSI paradigm? (relative impact and cost in time and money). What **intrinsic** characteristic(s) of digital electronics make the now-classical VLSI masking/layering technology so effective?
- (b) Do these elements apply to other manufacturing sectors, such as electro-mechanical manufacturing?
- (c) Focusing on rapid prototyping, are there manufacturing processes and technologies in which the VLSI paradigm holds, based on these key elements?
- (d) What are target industries for implementing the VLSI paradigm?
- (e) How can the VLSI paradigm be transferred to an industry? Research efforts? Infrastructure? Industry/university interaction? Demonstration projects and products?

#### The VLSI Paradigm

Some of the key elements of the VLSI paradigm that should be considered in examining the possibility of transfer to other manufacturing sectors are:

- (1) An enormous variety of VLSI products (having a large dollar value) can be built using the basic VLSI design methodology and a given industry-standard process.**

(“Given” in the sense that the process is the foundation stone on which the variety of products is built and “standard” in the sense that different suppliers use similar process equipment and sequences to make up the process which can manufacture designs using industry-wide design rules.)

- (2) The manufacturing process for the VLSI product uses material layering.**

The product is created by a sequence of material deposition and material removal steps resulting in a three dimensional object with the desired properties.

- (3) There is a clean separation between the VLSI manufacturing process and the design efforts that define the many products manufactured using that process. Further, the process is insensitive to the product design to be manufactured.**

As pointed out in the text by Mead and Conway , “...there is a clean separation between the processing done during wafer fabrication and the design effort that creates the patterns to be implemented”. The process is pattern insensitive. All of the uniqueness of a VLSI product is embodied in the mask set. None is in the process used to build a particular product as well as many others. Form (layout) and function (logic at speed) are uniquely related through the process used so that given the masking and knowing the process, the function is fully specified. It is like manufacturing dollar bills: the same paper, the same inks, and the same process are used but the value

of the bill is established by the configuration imprinted on its surface. In VLSI, a series of such layering steps is used.

**(4) Process constrained design is implemented.**

Mead and Conway note that the separation in (3) requires a precise definition to the designer of the capabilities of the processing line and is usually expressed in terms of geometrical constraints called design rules. Design rules appropriate to the process used are embodied in the layout software and libraries. Design rules insulate the designer from concern with process details and embody all of the constraints on layout that are imposed by the process. Conformance to design rules provides proof of "design for manufacturability," i.e. if the designer obeys the design rules (ordinarily enforced by the CAD system), he is guaranteed to produce a design manufacturable by the process. Conformance can be checked automatically by applying a design-rule-checker program to the software description of the mask layout. Stable design rules encourage the development of extensive design libraries consisting of the precise conforming layouts of a wide variety of logic building blocks.

**(5) The focus of the VLSI design community is on tool hierarchies and automation of the design activity.**

Process improvements are embodied in the next generation of design rules and are of less immediate concern to the designers. Digital product development is a hierarchical process, going automatically from a behavioral description of the product to the mask set and the test vectors. The design process starts with the initial behavioral description and proceeds to a functional description (partitioned system elements in block diagram form) to a structural description (logic diagram and net list) to a physical description (building blocks identified and interconnected). The physical description is then translated into the mask layouts. With available design software and hardware it is practical to implement error-free digital designs for products of million transistor complexity.

Analog products are in transition to an automated design methodology at a lower level of complexity. There are difficulties with the lack of uniqueness of the transformations leading from analog behavioral descriptions to mask configuration and with the tendency of the analog design community to implement analog devices with performance close to (if not beyond) the limits of the process capability. There is also a lack of standardization of analog processes across the industry. BiCMOS is a less competent analog process that is being used for building VLSI parts with nominal analog and full digital capability. The BiCMOS process is becoming standardized across the industry.

**(6) VLSI digital design and performance capability have encouraged the use of digital system implementation wherever possible.**

Today system designs take analog inputs from the sensors, convert them to digital form, process them in digital chips and, if appropriate, convert back to analog form for output. Many modern analog systems are, in fact, mostly digitally implemented. Examples also exist in the mechanical domain, e.g. fly-by-wire aircraft.

**(7) Virtual rapid prototyping using process and product models is replacing physical implementation of new designs for validation.**

Simulation tools and field programmable logic elements make it possible to avoid laboriously building prototypes, populating breadboards and evaluating system hardware as a first step in developing a new product. Multiple cycles of learning can be gained rapidly using such "virtual" prototypes so that product designs can be optimized before being put on the market.

Mapping the VLSI Paradigm

Having identified these key elements constituting the VLSI paradigm, can we now map them to the electromechanical manufacturing industry? Which of these mappings are the most critical ones and which are least important? Which are the most difficult to achieve and what is the cost/time to get there?



VLSI Elements	Electromechanical Mfgrg Equivalent
(1) Large number of products (designs) built from a given industry-standard process.	(1) Are there mechanical fabrication processes of such versatility that each process will permit a wide range of products?
(2) The product is built up by a layering manufacturing process in which material is deposited, defined and the excess removed, resulting in a three dimensional object.	(2) What processes allow the manufactured part to be produced by a series of layering steps, gradually growing material to the desired three dimensional shape? Are there materials technologies that do this?
(3) There is a clean separation between the VLSI manufacturing process and the product design effort and the manufacturing process is insensitive to the product design.	(3) Can the normal mechanical process plan be split into two parts - one an invariant associated with the mfgrg process and the other variable and depending on the nature of the product design.
(4) Process constrained design (design rule constraints that insure manufacturability of the product, not necessarily functionality which is validated using simulation)	(4) Are there design rules for mechanical mfgrg that are sufficient to ensure manufacturability? What is the impact of fixturing changes? Are they equivalent to process changes?
(5) Hierarchical tool sets for design and design automation. Tool sets evolve to permit designers to work at higher levels of abstraction.	(5) Can we create equivalent design tool hierarchies for electromechanical design?
(6) Analog/digital design implementation	(6) Must mechanical parts be defined and built in analog fashion or is a digital approach possible?
(7) Virtual rapid prototyping without building physical models	(7) Can we develop and use virtual rapid prototyping techniques to replace the need to build physical prototypes (using modeling, simulation, virtual reality visualization, etc.)?

## **ADDITIONAL QUESTIONS FOR THE WORKSHOP**

1. Are there some manufacturing processes and materials definition technologies as used in the layering process that are especially amenable to the VLSI design methodology? Which are they? What products can you manufacture using those processes?
2. How valuable is a shift to virtual prototyping for electromechanical products? What needs to be done to make it a reality? Are there specific aspects that are more valuable or less difficult so we can start with them?
3. VLSI techniques are being applied to the design of micromechanical structures. Is this likely to result in a significant gain in the use of computer tools for making mechanical products? What range of mechanical products can be built using this technology?
4. What infrastructure would be needed to support the application of VLSI design methodology to other manufacturing processes? What resources would be needed to put that infrastructure in place? Costs? Time? People?
5. By analogy to the growing digitalization of the VLSI world, are there design methodology changes that are needed to make manufacturing in general follow the VLSI paradigm? How can we support the development of such a digitalized manufacturing activity?
6. What rapid prototyping processes are there with the versatility to generate a wide variety of products by simply changing the product design and how can we build a VLSI-equivalent approach around them? Consider some examples: the plastics molding and plastics extrusion presses, the printing press, etc. See the list below of industries that are VLSI- and non-VLSI oriented and of their characteristics.

## **INDUSTRIES**

VLSI oriented	Non-VLSI oriented
VLSI microelectronics Lithographic arts Printing Plastic molding and extrusion Biotechnology Broadcasting & Cable TV Software Construction (with pre-fabs)	Automotive Aircraft Construction (not pre-fabs) Pharmaceuticals Agriculture Chemicals and Petroleum Refining Medicine & Health Care Retailing Teaching

## **CHARACTERISTICS**

VLSI oriented	Non-VLSI oriented
<ul style="list-style-type: none"><li>• One process, many products</li><li>• Extensive use of design history</li><li>• Elaborate set of design rules</li><li>• Multiple sourcing is practical</li><li>• Product uniqueness is in the configuration</li></ul>	<ul style="list-style-type: none"><li>• Each product, a different process</li><li>• Design history is of little use</li><li>• Processes use unique equipment</li><li>• Each process has unique capability</li><li>• Product uniqueness is in both process and configuration</li></ul>

## Appendix A - More on the Nature of VLSI

The VLSI example is one where product designs, unique to each company, have moved steadily toward very high levels of complexity and sophistication while the fabrication processes, also growing in complexity and sophistication, remained essentially the same across the industry. VLSI fabrication facilities grew in cost by factors of ten every decade so that few companies could afford state-of-the-art fab facilities. On the other hand, product design tools for each generation of a given manufacturing process were widely useful in several fab facilities. A system of design rules evolved which became standardized across the industry and which resulted in cross-fertilization of process capabilities among the foundries, whose customers insisted on their need for second sourcing of critical items. The existence of a common set of design rules across the industry also enabled "third party" design houses (without fab facilities of their own) to do state-of-the-art designs with confidence in the "design for manufacturability" of their products. These product and system designers were thus enabled to implement their designs without making the enormous wafer fab facility investment. Widely available design rules also clearly identified, for everyone in the business, what the industry pacing parameters were and encouraged fab facility upgrades to get to that pacing level of design rule capability. The use of design rules to decouple product design from process development is one of the seminal developments in the VLSI experience. It resulted in design multiplicity along with process unity.

It is worth noting that the earlier microelectronics technologies (TTL or NMOS chips on printed circuit boards) did not evolve into a VLSI-style design system for a variety of reasons. TTL and NMOS provided less perfect digital implementations in which there was less design margin (all "ones" were not at the high rail voltage and all "zeroes" at the low rail voltage). It was not yet possible for system level designer inputs to automatically be transitioned to layouts because the software and hardware did not exist. Physical breadboards were used as proof of concept because available simulation software was limited in capability and because the chips could be bought off the shelf and wired together point-to-point (cheaply and quickly).

The relationship between form and function (between mask layout and device performance) is well defined in the VLSI business since the process is essentially the same across the industry. (If it was not, we would need a separate form/function relationship for each process and a unique and expensive new design each time we changed the wafer-fab vendor) This decoupling of layout and process resulted in the development of extensive libraries of building blocks, all of which conform to those design rules. Library development is basic to the extensive use of design heritage in the VLSI business. Simulation tools evolved which enabled the electrical performance to be predicted accurately from the layout information. This means that the design loop can be closed [the simulated behavioral performance can be extracted from the design for comparison with the initial (specified) behavioral description]. It is not clear that closing the design loop is as easy when mechanical objects and structures are involved because, with a multiplicity of processes, the relationship between form and function tends to be process dependent and not well-defined. For example, an axle that is forged and an axle with identical dimensions that is cut on a lathe may look superficially the same but they will have very different durability. This raises issues about the type of process-specific simulation tools that are needed, more generally, to address form/function relationships in manufacturing.

Manufacturing is more generally a hodgepodge of processes and materials without the industry-wide design rules and design methodology that underlie the VLSI experience. We need to identify which sorts of manufacturing can be supported by efforts in the research phase, as the VLSI activity was successfully supported by research efforts in schools and in entrepreneurial activities. We will look for a model for product manufacturing which would be amenable to such support. For example, building objects by defining a succession of images in layers defined lithographically as suggested by Weiss et al of CMU<sup>10</sup> is an approach that might result in products that can fit the VLSI model. Are there more broadly applicable manufacturing technologies that can be supported? What products can

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<sup>10</sup> L.E.Weiss, F.B.Prinz, D.A.Adams & D.Siewiorek, "Thermal Spray Shape Deposition", *Journal of Thermal Spray Technology*, Vol. 1 (3) September 1992, p.231.

be manufactured economically using this layered fabrication process? What is the role of new materials and new processes?

We should also seek new ways to apply the tools that were developed in the VLSI business. For example, the VLSI behavioral modeling capabilities could be seen as a basis for creating virtual models of the mechanical products ("virtual rapid prototypes") which can be operationally tested, customer evaluated and modified to meet market needs, all without tooling up to build physical prototypes. Another example: these modeling techniques could also be used to improve the effectiveness of our production lines by first simulating the production activity and then adjusting the line variables until the manufacturing flow is optimized. Conceptually these two examples correspond to "virtual prototyping" and "virtual manufacturing."

In short, this workshop seeks to identify those techniques that are well adapted to supporting new manufacturing capabilities and to focus our efforts on getting these techniques defined to the level of capability needed for use by industry. This means research to solidify the concepts, education to make them widely available and encouragement for entrepreneurial implementation of the concepts in "industrial strength" form.

Although these computer-based design and manufacturing techniques cannot, by themselves, assure long term manufacturing success, a continual succession of nimble entrepreneurially driven advances is likely to result in product leadership. Such leadership can generate patents and intellectual property rights that will provide a decade of protection for the manufacturing innovations. The innovator can then focus on building new markets and on strengthening the tools that enabled him to serve his existing markets so effectively.

## Appendix B - A History of VLSI Development

The VLSI (very large scale integration) industry was an outgrowth of the transistor and integrated circuit activities of the nineteen-fifties and -sixties. Integrated circuits were seen initially as a way of putting more components in a silicon chip to reduce assembly costs and a way to improve performance by reducing parasitics and cross-talk. Soon the effectiveness of replacing the resistors and other passive components in the integrated circuit by more transistors became apparent (transistors took less chip area than the passive elements) and digital applications took off. Small entrepreneurial IC firms led the changes. Since the entrepreneurial chip designers did not have the desire to develop efficient wafer-fab production equipment, they found small equipment-oriented entrepreneurs to facilitate their production lines and they located in Silicon Valley to take advantage of the initial concentration of IC houses and equipment suppliers in that area. (The larger semiconductor companies did their own equipment development in-house, at that time.) With so many companies in the area, there was a regular traffic of experienced process engineers and technicians among the firms and major new process developments spread rapidly.

Design activities also benefited from the movement of technical personnel between companies. The pre-VLSI design methodology is described below. Initially the designers/engineers defined the circuit schematic and built breadboards to prove-out the circuit. Specialized layout draftsmen converted their circuits into multilayer circuit drawings. Specialized rubylith cutters converted the multilayer drawings into single layers for each of the mask levels. The product engineer defined the process that would be used with this mask set to build the product. This design cycle is similar to today's design cycle for mechanical product manufacturing where the product is designed, a machinist sets up equipment to build a prototype, and an equipment designer defines manufacturing processes to build it in production. The IC designer began to relinquish the process design responsibility since the TTL process, for example, was already well-defined in the industry and the IC designer was limited to minor tweaking of the process to meet the product specification. In the VLSI business today, by contrast, there is a standard process across the industry and standard materials and processing equipment are used at each step.

Design rules were evolved for each of the VLSI fab facilities that provided the designer with assurance that his design met stringent standards for "design for manufacturability" without testing the design by building prototypes. The growing importance of the design rules (which became the basis for the designer's confidence in his chip design and in his vendor's capability to build it) resulted in increasingly sophisticated techniques for establishing critical design rules based on elaborate process capability evaluation efforts. Design rules were ultimately established by running several lots of specially designed test wafers through the fab facility to evaluate and insure process capability on a statistical basis. The separation of design from manufacturing through the use of design rules is one of the seminal developments that made the VLSI industry so receptive to entrepreneurial design activities.

Improvements in design technology were transferred rapidly among companies (along with the engineers who used them). However, the specific layouts, which were clearly the intellectual property of the innovator, could not be brought along. Attention focused on reproducing the circuit in a slightly different configuration so it could be marketed. The use of locally designed building blocks to get the desired circuit performance became common. These building blocks soon were the stock-in-trade of every layout draftsman and became more elaborate every year, going from single transistors to elementary gates to flip-flops and registers. The circuits were originally susceptible to errors when they were pasted together in drafting and the interconnect lines which were long and numerous were sometimes connected incorrectly.

The growth of work-stations for drafting made it possible to incorporate the design building blocks in software where they would be immune to errors. Software for identifying design rule violations became available and was used to check out the building blocks before they were admitted to an approved cell library. An accurate interconnect was obtained by having the computer route lines according to a net list. Initially the layout programs needed to be supplemented by manual placement of building blocks and manual routing of the last five or ten percent of the interconnect lines, but the greater part of the interconnect net was free from human errors. The layout capabilities of computer

routing programs improved with better routing algorithms and better automated placement programs. Design rule and net list checking were applied to the interconnect network before committing the chip to masking (a substantial investment).

The existence of design rule sets unique to each fab facility challenged third party designers to find common rule sets so that they could multiple source their designs. Eventually this evolved into an industry-wide set of design rules for each generation of geometries. This standardized the processes and the facilities without squelching invention (to improve yield) or delaying process evolution to the next generation geometries.

The level of abstraction for design was steadily rising, from transistor to gate to register to major building block. (Bit-slice processors and even core microprocessors were soon available as building blocks.) In the nineties, design of complex circuits is done in behavioral form at the system level by a system architect. Software is able to partition, synthesize (and optimize), simulate and define mask levels with a minimum of human involvement. Building blocks come in parameterizeable form so that  $m \times n$  registers can be created by the software system. Circuit designers are required only when new building block capabilities are called for. Many of these steps in going from a behavioral description to a final layout are incompletely connected at this time so that human intervention at the interfaces may be required, but there are CAD framework specifications so that everyone knows what the interfaces are supposed to accomplish and how the data is formatted for each stage. Software languages, like C++ have evolved that make it less difficult to deal with sophisticated objects (like the elaborate building blocks and their associated performance parameters).

The ultimate guarantee of product design accuracy is the extensive use of simulation tools to assure function and performance at the building block level and at the behavioral level by tying together all the functional and timing information about the building blocks. Multiple cycles of simulation at various levels of abstraction assure that the performance of the "virtual prototype" in the computer will match the performance of the real product when it is masked and fabbed. The earlier practice of bread boarding chips is often abandoned. In cases where bread boarding is regarded as essential to product feature evaluations at the system level (with all the sensors and actuators in place), the use of field programmable gate arrays and field programmable interconnects makes possible rapid product improvements that can be implemented in product chips when the system design is finalized.

In parallel with the elaboration of the VLSI design system there was an evolution of the wafer fabrication equipment that focused on geometry scaling (reducing the size of the design elements). The processing equipment became more elaborate, more sophisticated and more expensive. Furnaces for impurity deposition and diffusion were replaced by ion implanters that provide precise control of impurity distributions near the surface for these increasingly shallow devices. Accurate simulation models for the process itself encouraged focused process and process equipment improvement efforts.

Masks were built using electron beam exposure systems that could define geometries to well below a micron. Photolithography was performed on steppers that used high numerical aperture lenses to provide multiple exposures per wafer at controlled spacings. The light source used for exposing the photoresist on the wafer moved steadily to shorter wavelengths to permit definition of finer lines. Larger wafers meant more chips per wafer (resulting in considerable cost reduction). However, larger wafers also required retooling the fab facility which facilitated going to the next new generation of geometries. (Three inch wafers for two micron geometries, four inch wafers for one and a half micron geometries, six inch wafers for sub-micron geometries, etc.) These new process equipments developed by vendors of specialized equipment who sold to all the competing wafer fabrication facilities. New equipment (like new steppers) could bring revenues of hundreds of millions of dollars to the vendor who had the best machine, but the lead passed from supplier to supplier and no one could maintain a lead for more than a few years without continuous equipment improvements and redesigns. The use of external process equipment vendors and the proliferation of third party designers resulted in an industry based on standard processes and standard design rules.

Over the decades a system of entrepreneurial funding developed in which suppliers of venture capital (also located in Silicon Valley) would fund start-up teams with new product concepts and new product implementation techniques. As these new enterprises were started, public offerings in the stock

market provided rich returns to the entrepreneurs. This system created a constant supply of individuals and teams who wanted to “rock the boat” and it empowered them to introduce new product concepts and new approaches to design and fabrication.

These drivers of innovation did not insure the VLSI industry against loss of manufacturing activities to off-shore suppliers. The labor intensive activities, such as assembly and test, migrated to low labor cost areas. However, first samples were built locally to reduce the time required to turn a new design into a market-place product and the time required to finalize the test program and prove the reliability of the product. Similarly, some mass market products, like dynamic random access memories (DRAMs) moved to sophisticated overseas suppliers (in Japan) who could supply the products at lower cost once the design was defined and the process technology proven. The more rapidly moving parts of the VLSI market (e.g., specialized communication chips and microprocessors) stayed in the US. where market feedback was quicker and could be used to keep the products at the competitive forefront. (As an aside, it is worth noting that the focus of the Sematech activity has been to improve the industry standard process and the equipment used to operate that process. Since those improvements benefit everyone, almost everyone supported Sematech. The implicit message is that the real competition in the VLSI business is in the product definition, design and development areas, not in process improvement.)

The interlocking VLSI design, fabrication and funding systems described above (along with educational and industrial infrastructures) have provided the U.S. with a position of leadership in a major growth industry for several decades. Even when there was real concern that the Japanese were capturing the semiconductor business (in the mid-eighties), the system actually worked to maintain American strength in the leading edge portions of the business.

**Acknowledgment:**

The authors wish to express their appreciation to the reviewers of earlier versions, and especially to Bob Sproull, Herb Voelcker, Fritz Prinz and Dan Siewiorek for their comments. Many of their their suggestions have been incorporated in this text.



### 3.4. POSITION PAPERS

#### 3.4.1. POSITION PAPER BY CARLO SEQUIN

##### **CAN THE VLSI CAD REVOLUTION BE REPEATED IN MECHANICAL ENGINEERING ?**

**Carlo Sequin  
Univ. of California, Berkeley  
April 18, 1994.**

The Dream:

To repeat the VLSI CAD and manufacturing revolution in other fields: e.g., mechanical engineering, architecture, others ... ?

Special Properties of VLSI:

- \* Top down design.
- \* Reuse of low-level components.
- \* Complete simulation, verification.
- \* Rapid prototyping.
- \* Inexpensive, reliable, high-volume manufacturing.

VLSI vs. ME-World (1):

- \* VLSI systems don't "DO" anything, they just "reason".
- \* Logic has neat abstractions, can be done near zero power levels.

BUT:

- \* Function of mechanical systems is much richer,
- \* Power is always a primary concern.

VLSI vs. ME-World (2):

- \* Logic has a universal elementary component: the NOR gate;  
this allows a building block approach.
- \* Frequently used clumps of gates: EXOR, MUX, Decoder, ALU, Register...  
are provided for efficiency and economy.

BUT: It is hard to find a Building Block Approach in ME !

- \* Example 1: MECCANO: is a child's toy;
  - parts are too expensive, assembly is too expensive,
  - system is not flexible enough to build practical things.
- \* Example 2: 19th-century factory:
  - components are the machines;
  - limited applications of modularity.

==> Neither example is suitable for automatic "manufacturing" .

Single- vs. Multi-Functionality of Parts:

- \* Lowest VLSI components (FETs) do ONE thing: switch.

BUT:

- \* ME parts normally carry many useful functions:
  - provide stability, translate forces, contain fluids,
  - carry current, shield out fields, dampen vibration ...

ME-Designers vs. VLSI-Designers (1):

- \* (V)LSI designers are used to work with a limited set of standard parts, e.g., TTL library.
  - \* These parts are rather universal, robustly designed to fit together reliably at the system level (if a few rules are observed),
  - \* They give predictable performance.
- BUT:
- \* ME-designer wants/needs more design freedom.

ME-Designers vs. VLSI-Designers (2):

- \* VLSI designers want to get the job done.
  - \* They want a chip that works properly first time.
  - \* They accept reduced performance, increased chip area.
- BUT:
- \* ME designers will NOT accept half the performance or 4 times the weight!

VLSI Design Characteristics:

Provides clean separation of concerns at different abstraction levels:

- \* Layout: Reasonable fabrication yield, circuit performance.
- \* Symbolic/sticks: Spatial organization for minimal area and delay.
- \* Switch: Signal polarity, delays, RC-timing.
- \* Logic: Fan-out and timing, elimination of races.
- \* RTL: System operation, global timing, execution parallelism.
- \* Function: Proper functionality, formal specification {hard}.
- \* Behavior: User's desires, informal characterization {very hard}.

Potential Synthesis Tools for Mechanical Engineers:

EXAMPLE:

- \* INPUT: "Design a gearbox with a reduction ratio of 12 : 35,
  - with maximum dimensions (x,y,z),
  - with input / output shaft positions specified,
  - with a weight less than ...
  - for a maximum torque of ..."

\* OUTPUT: The geometry of the gearbox.

OR:

- \* INPUT: "Design a heat exchanger for 20,000 BTU,
  - in a space less than (x,y,z),
  - for minimal cost ..."

\* OUTPUT: blue prints, parts list.

{This is still only equivalent to (VLSI) module level}

Are there Useful Conceptual Design Tools for Mechanical Engineers ?

EXAMPLE:

- \* MechEdit, a "stick-level" tool for planar linkages.

==> raises little excitement with my ME colleagues.

Mechanical Engineers are more interested in:

- \* obtaining a 3rd order model of a spiral spring to determine exactly at what RPM the valve-cam-follower loses contact with the cam;

OR:

- \* how the curvature of the cylinder surface head in a combustion engine affects speed and completeness of the burn process.

Mechanical vs. Electrical Design:

- \* More simultaneous concerns in each part:

mechanical strength, aesthetics, sound isolation, thermal flux, ...

- \* These concerns cannot be separated, cannot be simulated simultaneously. MOREOVER:
- \* A much richer catalog of solutions exist for many basic functions:  
e.g., for connecting: welding, gluing, riveting, bolting, one piece, ...

#### Re-Use of Standardized Manufacturing Processes ?

If in ME we cannot reuse finished parts easily,  
perhaps we can reuse the design / fabrication process for such parts.

I.e., can we find standard fabrication processes  
that always go through the same standard steps  
described in a parameterized script,  
and are fully described by a set of parameters ?

A new part / product would then be defined by the standard process  
and by a special set of parameters,  
or by a special geometry (e.g., masks).

A potential candidate process: sheet metal cutting, bossing, bending.

#### Better ME Conceptual CAD Tools Are Needed:

- \* To visualize the result of a manufacturing process;
- \* To exercise the final configuration of a complicated assembly;
- \* To debug the process sequence of an assembly.

#### CAD Tools for Conceptual Design:

They should provide:

- \* High-level concepts and operations,
- \* Suitable (adjustable) abstractions,
- \* Quick and easy "sketching",
- \* Smarts to "understand" sketches,
- \* Capture intent of designer,
- \* Possibility to simulate (explore, play),
- \* Possibility to analyze (evaluate, verify),
- \* Possibility to compile to lower levels.

==> To what degree are such tools available / practical for mechanical design ?

#### Some Critical Issues We Should Discuss at the Workshop:

- \* What are the right type of parts for which we can hope to find  
a VLSI-like design and fabrication process ?
- \* Are state-of-the-art systems such as jet-engines or smart missile heads  
really the right target ?
- \* Should we perhaps look at appliances such as  
shavers, toasters, blenders ?
- \* Can issues of reliability, fault tolerance, expected life-time  
be separated out from the design and fabrication process,  
to the degree that this is possible in VLSI ?  
(And dealt with generically, independent of the specific product,  
just dependent on the fabrication process and the materials used ?)

### **3.4.2. POSITION PAPER BY ROBERT F. SPROULL**

#### **DIGITAL INTERFACES TO FABRICATION**

**Robert F. Sproull**

**Sun Microsystems Laboratories**

**May 2, 1994**

There is tremendous power in designing and implementing suitable digital interfaces to processes of all kinds, including fabrication processes. In what follows, we will speak of "the designer" and "the fabricator," but the two players might take on different names or roles in different settings. Some of the obvious advantages of "digital orders" are:

- The ability to communicate fabrication orders from one site to another, either because design and fabrication are carried out at separate sites, or because the order must be filled by a different fabricator than originally intended.
- The ability to broker the fabrication job to one or more vendors who offer the same interface definition. Part of this process might include soliciting quotes.
- The ability to store an order to be used later. For example, spare parts need not be fabricated in advance, but if the digital order for each part is saved, it can be used later, as needed, to fabricate replacements.
- The ability to automate a process that verifies that the order conforms to certain specifications or design rules; in effect, to form an agreement between requester and provider that the job being requested is reasonable.
- The ability for participants on both sides of the interface to enjoy direct benefits of further automation, e.g., a designer who can use CAD software to prepare a design, and a fabricator who can prepare a process plan automatically. Importantly, the digital interface allows composition of fabrication processes, i.e., in order to fill a complex digital order, a fabricator can perhaps use automatic software to prepare an order for a sub-assembly that will be filled by a different fabricator.

The interface to any digitally-driven machine, such as an NC mill, might seem to satisfy these properties. Without additional requirements, however, we would have a profusion of disparate interface definitions that do not interoperate, with the consequence that neither designer nor fabricator could afford to invest in the software or operational discipline to make use of them. So there are some additional requirements:

- The interface definition should be as simple as possible, easily understood, and easily handled (e.g., ASCII in preference to binary). Since many people will have to learn and understand the interface definition, simplicity is important.
- The receiver of a digital order must be allowed no discretion in executing the order, except as permitted by some previously agreed "design rules." As long as the fabricator builds a part that matches the digital order, subject to variations permitted by the design rules, he has performed correctly. A consequence of this requirement is that fabrication is predictable, and the design rules carry enough information so that the designer can do all the analysis required to determine what the fabrication process will produce from the order.

In addition, there are some desirable properties of digital interfaces. The first two, device independence and process independence, allow an order, once prepared, to be routed to different devices or vendors for fabrication.

- Device independence. In order to prevent a proliferation of interface definitions, a few interfaces that abstract away from inessential differences among devices is preferable. If the abstraction hides any device differences that would lead to design-rule violations, the fabricator must apply corrections to the digital order so that the device will make the intended result.
- Process independence. Similar to device independence, process independence tries not to specify the fabrication steps used, or the order in which they are performed.

- It is preferable if the interface defines the intended result, not the process used to achieve it. Not only does this technique give the fabricator needed flexibility in choosing a fabrication method, but it frees the designer from having to know details of fabrication processes.
- While not absolutely essential, there should be algorithms that the fabricator can use to process the order into a form that directly controls the rest of the fabrication process. In other words, part of the motivation of digital interfaces is to avoid human errors during fabrication. In a few cases, however, human intervention is desirable. For example, when designing a new digital interface, or when refining design rules, it may be helpful to do some or all steps manually, in order to better understand how full automation should be done, or whether it is required.
- Insofar as possible, do not make the digital interface depend on many detailed parameters or libraries that must be known to both designer and fabricator. The reason is simply that the designer and fabricator may, over time, come to have different versions of this data, or some fabricators may not have the required library. (These problems have shown up in PostScript, which depends on the printer having in its database the detailed definition of a font requested by a PostScript file. If the printer does not have the font, or does not know the character widths exactly, the printed page will not meet the designer's expectations.)
- It's helpful if the design rules can be expressed in a digital form, so that analysis and synthesis tools used by the designer can adapt quickly and correctly to changes in the design rules promulgated by the fabricator.

The points listed above are generalizations derived from experience with the CIF interface to VLSI fabrication, and with several page description languages (predecessors of PostScript) for instructing printers of many sorts.

## Detailed Lessons from the VLSI experience

The university involvement with VLSI design (exemplified by the "Mead-Conway" approach) was made possible by separating the design and fabrication of integrated circuits. No university could afford a commercial fab line. Moreover, Carver observed that fabrication of integrated circuits is a "pattern insensitive process," i.e., the steps in the production process do not depend on the patterns being laid down on different layers (the masks). So a very wide variety of designs (patterns) could be fabricated in a uniform way, even combined on a single mask set. Carver's key contribution was a simple set of design rules that constrained designs so that they could be fabricated by a wide range of vendors—essentially a "universal design rule set" for nMOS (at the time).

As a practical matter, however, the designer had to give up a fair amount of "performance." In order to do designs that could be fabricated by a wide variety of vendors, he had to use quite loose geometric design rules, in some sense the "least common denominator" of many fabrication processes. Moreover, fab vendors were unwilling to make many guarantees about electrical performance (because the university designer did not represent significant income), and so the usual wide manufacturing variations in electrical behavior of transistors, wires, etc. had to be widened further by the designer who wanted his chip to work. The result was that the designer gave up quite a lot of performance; perhaps too much to design "commercially competitive" parts this way. But university designers could explore a wide range of exotic system designs that did not interest industry.

The commercial adaptation of this idea tightened the design rules, so that the designer would lose less performance across the design-to-fab interface. When a designer signed up with a specific fab vendor, she was given vendor-specific electrical and geometric design rules, simulation models, and (usually) access to vendor-specified rule-checking software. As you might imagine, it is hard(er) to get the tighter design rules to reflect accurately what the fab process can build reliably, and there is a *lot* of iteration, tuning, and just plain blundering in the process of getting designer and fabricator in harmony. Moving a design to a new fab vendor is a major chore, because the design rules will change.

Another designer/fab interface grew up in the commercial world as well, around ASICs (usually gate arrays or standard-cell layouts). The designer prepares a schematic of the circuit, using macros or

building blocks supplied by the fab vendor. The "net list" is sent to the fab vendor, who uses internal CAD software to devise a placement for all the components, a routing for all the wires, and a calculation of the delay introduced by each wire. The delay file is transmitted back to the designer, who uses another CAD program to do either static timing analysis or simulation to see if the delays introduced by the layout cause the design to misoperate. While these steps sound simple, they aren't. Different CAD software will use different "libraries" of macros, and not all fab vendors will support all library formats. Libraries are notoriously full of errors (who knows why; one can imagine a semi-automatic library-building process driven by process characterization, but it's rarely done). And the interpretation of timing information differs from simulator to simulator, so that the designer is usually obliged to run the same simulator software that the fab vendor uses. So the notion that there's a simple, standard, digital interface between designer and fab is seriously eroded.

To make matters worse, some fab vendors simply "change the libraries" seemingly without warning. They change the fab process, change the libraries, and push re-work back on the designers. This is an abuse of the process as originally envisioned. But it happens.

Most of this messiness is unnecessary; it's an outgrowth of haphazard growth of the CAD industry and of standards for interchange of CAD information. Note that for some integrated circuits, the design and the fabrication process are so tightly linked that there is no pretense of a "standard interface" between design and fabrication. DRAM chip designs, for example, depend on every detail, electrical and geometric, of the fab process. A high-volume product that depends on process details won't separate design and fabrication, but will tune both to get a competitive product.

Summary: You give up performance to separate design and fabrication. It won't work for all designs.

## **What about mechanical parts?**

What manufacturing processes are driven almost exclusively by two-dimensional geometry/pattern data, as is VLSI? Printing is clearly one, and indeed one could imagine a completely digital interface to printing (e.g., PostScript, plus additional information having to do with things like paper selection, binding, etc.). Some printers operate *almost* this way today, but a widely-adopted interface to the entire printing process does not exist.

There are some mechanical fabrication processes that are pattern-insensitive, e.g., the raster-scan powder machines, or the laser-curing machine (SLA). These may have quite restrictive design rules that lead to, for example, a requirement that the designer design support structures to accompany the part he wants (e.g., for the laser curing, the part must be well connected at all times during its growth). In these cases there is an algorithm to convert from the geometric description to a form that will drive the fabrication machine. (But is there a "design rule checking" algorithm? That may be harder.)

Even when the fabrication process is not pattern-insensitive, there may be algorithms to convert from the description to tool controls, e.g., 2 1/2 D milling, sheet metal cutting and scoring, making signs by milling laminates, etc. Different tolerances or surface finish can be achieved by algorithmic adjustments to the machining plan, such as changing speeds and feeds. If there are no general algorithms to plan fixturing given only the finished part description, the digital interface can require the designer to know something about the fabrication process and to provide information about fixturing. For example, one could:

- Use design rules to limit the class of parts to those that can be automatically fixtured, e.g., clamped, or bolted through identified "fixture bolt holes" into a base. The digital interface would specifically identify clamping sites or fixture bolt holes. Geometric design rules would then limit how close to a clamp or bolt a cut can come.
- Make certain kinds of fixturing a part of an "abstract fabrication process," i.e., reveal certain aspects of the process to the designer, so that all the fixturing can be planned and designed, but retain enough flexibility for the fabricator to do things in different ways.

Summary: Think of the problem as "how do we drive a fabrication process from entirely digital specifications?" rather than the narrower: "can we fabricate a desired part knowing only the detailed description of the part, and nothing else?"

### **3.4.3. POSITION PAPER BY FRITZ PRINZ**

#### **UP SCALING OF VLSI FABRICATION IDEAS BY SIX ORDERS OF MAGNITUDE IS STARTING TO HAPPEN**

**Fritz Prinz and Lee Weiss  
Carnegie Mellon University  
April 26, 1994**

Traditional mechanical manufacture, VLSI fabrication, and emerging new rapid prototyping technologies are briefly considered from different perspectives.

#### **For Centuries**

the majority of manufactured goods have all been built by the 'shape first assemble later' paradigm. Individual components are cast, molded, stamped, milled, turned etc., and then assembled into functional products. For example, the automotive, aerospace, and until recently the Swiss watch making industry alike have adopted the same methodology. Different only by the rate of production, the size of the components, and to some extent product complexity, these industries have achieved remarkable levels of performance and reliability. The automotive and aerospace industry are likely to thrive on this paradigm for a few more decades. The traditional Swiss watch making industry on the other hand has faded because the demand for packing more and smaller components into the same volume had reached the limits of economically handling small parts with automated devices. A much better way of recording time was made possible through electronics. IC fabrication technology ultimately replaced traditional mechanical watches.

In sharp contrast to traditional mechanical manufacture, the IC fabrication industry has been assembling logic circuits based on a different paradigm. Thin layers of metal and ceramic materials are sequentially deposited and shaped. Deposition is done with techniques such as CVD, PVD, and sputtering. Shaping occurs through various lithographic, masking and etching techniques. The properties of individual layers are further modified by oxidation, doping, and heat treatment. The key difference to mechanical manufacturing is that shaping and assembling occur simultaneously and incrementally.

#### **During the eighties**

the research community started to apply IC, LSI, and VLSI fabrication technologies to domains other than mere logic devices. The feasibility of building small sensory devices, actuators and motors was demonstrated by a number of MEMS (Micro Electronic Mechanical Systems) researchers. The feature size of these devices is one or two magnitudes below the size scale where the Swiss watch making industry left off, but one or two orders of magnitude bigger than the resolution achievable in today's VLSI fabrication plants. Mechanisms can also be built using sacrificial support material to separate individual components during the fabrication process. Another important characteristic is that most artifacts built with VLSI fabrication techniques have rather flat geometries. Incremental layer building inherently facilitates the construction of devices with high eccentricities normal to the building direction.

Independent but parallel to the developments in MEMS another research community started to generate 3D mechanical structures by decomposing CAD models into thin cross sectional slices and then building one cross section on top of the other embedded in complementary shaped sacrificial supports. Various embodiments of this method called layered manufacturing, or solid freeform fabrication, are commercially available and well publicized. The most important limitations of these technologies to date are related to material variety, material quality, geometric accuracy, surface finish, and rate of production. Major benefits stem from the ease of planning even for highly complex shapes. Analogies of these methods to VLSI fabrication are obvious. In both instances objects are built by incremental material deposition and simultaneous shaping of layers. The range of feature sizes in layered manufacturing today is typically hundreds of microns to hundred thousands of microns.



## In Traditional Mechanical Design

a top down design process where functional specifications can be, step-by-step, translated into physical objects is difficult to achieve. This can be attributed to the lack of a clear-cut functional decomposition of most mechanical components. Also, bringing manufacturing constraints upstream into the early design stages proved to be more difficult than anticipated by the design community a few years ago. Problems are primarily due to the difficulty of expressing manufacturing knowledge in the form of simple design rules. This in turn results from a lack of proper abstraction schemes in mechanical design which are significantly more difficult to develop in a 3D mechanical world versus the mostly 2D world of electrical and electronic systems. Emerging feature-based CAD systems for mechanical design will ultimately facilitate a better representation of manufacturing knowledge and constraints. In the mean time mechanical design will remain highly iterative and subject to frequent trial and error procedures.

Top down design is much more prevalent in electrical and electronic engineering. Functional decoupling is routine and abstraction schemes to express rules for VLSI fabrication are well established. These rules are well integrated into VLSI CAD frameworks. In fact, successful VLSI chip fabrication would not be possible without the existence of hundreds of well integrated design and production planning tools into common environments.

Drawing analogies between the design of mechanical and electronic systems will always remain difficult. However, when only considering the production planning process for VLSI, MEMS fabrication, and layered manufacturing, striking similarities exist. In all cases the planning process occurs in a largely flat world which facilitates feature definition and automatic feature recognition from CAD representations. Hence, the complexity of expressing manufacturing rules and presenting them to the designer will become similar in both domains. Design/manufacturing protocols such as MOSIS for VLSI are likely to be established for layered manufacturing with comparable effort. Protocols such as the .STL format in layered manufacturing are severely restrictive today but represented the first step in this direction.

A bottleneck frequently encountered in traditional mechanical manufacture is part fixturing. Since parts made by layered manufacturing are always fully embedded in a support structure, planning and manufacturing of complex and expensive fixturing devices is largely eliminated.

## The 'Shape First - Assemble Later'

paradigm of traditional mechanical manufacture imposes important constraints regarding the geometry of individual components. For example, consider assembling a ship in the bottle. Conventional wisdom would strongly advise against the fabrication of such a configuration due to expected assembly interference problems. In layered manufacturing, however, decomposition of both the ship & bottle into thin slices followed by incremental and simultaneous build up of both components **poses no additional** planning complexity.

The benefits of removing traditional geometry constraints is illustrated with a practical example from the tooling domain. Injection molding tool cavities & cores frequently have cooling lines embedded to balance the heat flux. A skilled tool maker needs to decompose the tool design into sub components such that the cooling lines can be properly inserted when the tool is assembled. Lead times of several months are common in the tooling business due to the high degree of complexity in planning and building. Layered manufacturing potentially offers the opportunity to dramatically cut these lead times. Tools no longer need to be decomposed but can be built as a single entity with significantly less planning complexity. Early experiments appear to confirm this hypothesis.

The argument of relaxing or eliminating traditional geometric constraints through layered manufacturing can be extended further by imagining the manufacture of integrated mechanisms such as gear trains in a single process step. As in MEMS, layered manufacturing could achieve this because it also incorporates sacrificial support material. Current technologies are years away from practically realizing such ideas but appear worthwhile for further exploration. Direct integration of devices like sensors and micro actuators into mechanical structures during fabrication also appears attractive given the trend towards increased information content in future products. To achieve this goal layered

manufacturing technologies have to be extended over a wide range of materials. Resolution capabilities should be comparable to that of MEMS technology. In essence, a spectrum of deposition and shaping technologies are needed which can cover a feature size range from tens to millions of microns. Deposition processes need to be developed with rates commensurate with cost effective production. Candidate processes which have several orders of magnitude higher deposition rates than CVD and sputtering are plating, thermal spraying, welding, casting, layered deposition of powder and sheet material.

### **Improved Performance**

of mechanical design parameters such as stiffness-to-weight ratio can be frequently achieved through the use of composite materials. The limited application of composites in the past is largely related to prohibitive costs of producing complex shapes. Traditional fastening technologies as commonly practiced in metals has limited applicability due to low toughness of most composites. Joining composites with adhesives often requires the development of costly special purpose procedures. Fatigue life of components joined by adhesives often can not be guaranteed. What is needed is a technology which enables direct fabrication of composite structures with complex shapes. Layered manufacturing can potentially fill that need provided certain material quality limitations can be overcome. In particular, the adhesive strength between layers is likely to pose significant challenges in the future. Furthermore, internal stress build up due to temperature gradients, possible ( ~mismatch between layers, and incremental material shrinkage limits dimensional stability and strength of parts made by layered manufacturing.

These problems are well known in VLSI fabrication, obviously on a different size scale. Theoretical and experimental analysis techniques were developed to quantify and measure internal stress levels and predict mechanical strength. Also, research has been done to relieve internally built up stresses through selective heat treatment. The layered manufacturing community can largely benefit from that experience.

The next step in the evolution of composites will be the generation of truly custom tailored gradient-based structures such as components which are hard on the outside but tough inside. Again, such structures will only become feasible for practical use if we can successfully develop (layer like) fabrication methods that enable a direct link between CAD and cost effective production.

### **In the Future**

design and manufacture will be conducted by globally distributed, multi-corporate teams which reconfigure rapidly to generate and fabricate new products. Limitations regarding functional decoupling will frequently determine the degree to which design tasks can be geographically distributed.

Once a design is completed effective communication for prototyping or manufacture over the net will be important for the productivity of distributed design teams 'Over night' prototypes can significantly influence the direction a team intends to pursue Numerous reports on the use of layered rapid prototyping technologies over the net seem to confirm this. We anticipate a substantially larger impact once functional prototypes can be delivered within days rather than weeks or months which are common in today's development environments.

Communicating electronically complete designs for manufacturing has long been practice in VLSI design. In the past similar attempts in the mechanical domain have frequently failed since manufacturing difficulties related to part-specific tooling and fixturing could not be anticipated. Realistic 3D simulations will significantly help to envision downstream problems. However, decomposing parts into thin subsections and eliminating fixturing requirements all together due to full part embedding into sacrificial support structures is considered an even greater step towards decoupling the design from the fabrication process.

### **Summary**

The 'VLSI experience' has limited bearing on mechanical design. But significant analogies can be drawn between VLSI fabrication and the layered manufacturing processes of mechanical structures.

A number of planning, applied mechanics and materials science issues, though different in scale show striking similarities. Rapid prototyping experiences of layered manufacturing in industry indicate significant future potential. Substantial research and development efforts are required to enable layered fabrication of fully functional parts and assemblies. Progress can ultimately result in an expanded design space where many traditional geometry constraints are largely removed.

### 3.4.4. POSITION PAPER BY MICHAEL J. CIMA AND EMANUEL.SACHS

#### **SOLID FREEFORM FABRICATION AND NEW PARADIGMS FOR MANUFACTURING**

**Michael J. Cima and Emanuel Sachs**

**Mass Institute of Technology**

**April 22, 1994**

There is a fundamental parallel between the layer by layer construction methods used in Solid Freeform Fabrication (SFF) and the mask level by mask level creation of a VLSI device. There are also strong parallels at the unit process level with SFF analogs to many of the traditional VLSI processing steps as illustrated in the table below: The power of SFF techniques derives from the same source as the power of VLSI fabrication, the de-coupling between design and manufacturing, as recognized by Mead and Conway. As in the case of VLSI design, this decoupling takes two forms:

\* Complex 3-D geometries are decoupled by rendering as a stack of 2-D geometries (This feature is shared by all SFF techniques).

\* The geometrically localized building process allows for local control of the composition and microstructure of the finished product. (this feature is not shared by all SFF techniques).

<b>VLSI processing step</b>	<b>Analogous SFF technique/step</b>
CVD or PVD	Spreading new layers
Photolithography by wafer stepper	Solider
Photolithography by direct write	Stereolithography
Use of masks	Cutting masks in old MD* process
Ion implantation	Printing matter in 3DP
Planarization	Milling surface in Solider
Etching	Machining step in new MD* final removal step in all SFF

Solid Freeform Fabrication (SFF) techniques are largely viewed as methods for prototyping structures solid model descriptions of parts. The emphasis on prototyping stresses SFFs obvious applicability to reduction in product development time. Several commercial systems, have indeed demonstrated the utility of SFF toward helping designers. Most SFF techniques produce geometric forms which are either used for design evaluation or as patterns to be transformed into an engineering material by a secondary process such as investment casting. These applications take advantage of the geometric decoupling of the first bullet above

Historically, we can observe that the development of CNC machining provided the fertile ground from which CAD emerged. The authors believe that the opportunity to apply a design methodology based on the decoupling of design and manufacturing as tempered by design rules is the corresponding dramatic opportunity provided by SFF technologies.

We view two unexplored areas as having potentially larger impact on manufacturing. First, SFF methods are examples of microconstructive manufacturing which allows creation of components that can not be made by conventional methods. Second, some SFF methods can be developed to yield manufacturing scale production volumes. Both of these areas are surprising similar to VLSI design and production methods.

#### **Microconstructive manufacturing**

SFF methods rely on point-by-point construction of objects. Thus, one can envision components where both the macrostructure and microstructure are designed by computer. Never before have designers had complete freedom to design microstructures. We refer to this process as microconstructive manufacturing. Microstructure is usually developed within the confines of the manufacturing process.

Thus, designers must compromise component performance with manufacturability. SFF processes make it possible to vary the composition and structure of a component from position to position with complete freedom. Potential applications of such a technology are numerous, such as components with anisotropic thermal, electrical, or mechanical properties or microengineered porosity.

SFF methods can be classified into two general approaches; those that direct energy and those that deposit matter. Nearly all of the methods are based on laminated object construction. A layer of material is laminated followed by a pattern definition sequence. The layer pattern is defined by either writing with a laser or printing or extrusion of matter. The "tool" for directing the definition medium is either servo-controlled mirrors, as in the case of laser-based processes, or some type of printer, like that used in 3D Printing. Note that the tool path is confined to 2D slices of a 3D object. This feature distinguishes SFF methods from NC machining since tool path planning is greatly simplified. Secondly it is the first similarity to VLSI production methods. The layer-by-layer VLSI production approach is very similar. SFF methods do not have a direct analogy to etching, but the general deposition and pattern definition steps are very similar.

The various SFF methods are not equal in their applicability to microconstructive manufacturing. Clearly, those methods based on directing energy can not create point-by-point variation in composition within a component. Other types of microstructural variation are, however, possible using these methods, such as porosity variation. Directed deposition of matter eliminated the need for an analogous etching step as is done in VLSI. Etching is performed in VLSI

## **Manufacturing Scale and SFF methods**

The benefits of microconstructive manufacturing can only be realized when SFF methods can be used to mass produce parts. Currently the cycle time for most SFF methods is too long for broad applicability to manufacturing. An important exception is to use SFF method for making tooling. Tools for plastic molding or casting often have long lead times that SFF methods can greatly improve upon. We have, for example, made injection molding tooling by 3P printing, but many other tools such as EDM tools and die casting tooling are certainly possible by 3DP.

Direct writing of for pattern definition is a notoriously slow process even in VLSI technology. It is for this reason that most pattern definition steps in VLSI are mask type images where the pattern is defined at once. This approach is taken by Cubital, for example, where the photopolymer layer is developed by exposure to light through a mask. Rate can be increased in direct-write processes by parallel operation of many writing tools. The production rate of 3DP can be scaled up using multiple nozzle technology. Such scaling can apply to either a raster or a vector machine. Commercial ink-jet print heads are available with thousands of nozzles. Recently, such multiple printhead technology has been applied to 3DP and demonstrated a dramatic increase in production rate.

We believe that scale is an additional feature that must be considered in context of SFF and manufacturing. 3DP, for example, can be scaled up in the size of the component produced simply by building longer motion control hardware to move the printhead. The production efficiency increases with bed size since the printhead spends more time printing rather than spending time turning around.

### **3.4.5. POSITION PAPER BY MARK CUTKOSKY**

#### **APPLYING VLSI DESIGN AND MANUFACTURING PARADIGMS TO MECHANICAL DESIGN DOMAINS**

**Mark R. Cutkosky**  
**Center for Design Research**  
**Stanford University**  
**April 20, 1994**

#### **Abstract**

The question of applying ideas and paradigms from the VLSI domain to mechanical or electro-mechanical design and manufacturing has been debated innumerable times. My own position goes as follows:

1. VLSI design and manufacturing are a specialized domain. For any specialized domain, design rules and a CAD/CAM infrastructure can be developed if it is worthwhile from a design and manufacturing standpoint.
2. From a design standpoint, it is worthwhile if the need to manage complexity (e.g., to be able to analyze complex systems of many elements) outweighs the need to minimize functions such as size, weight, or thermal efficiency.
3. From a manufacturing standpoint, the infrastructure is worthwhile if there is a premium on obtaining access to a prototyping or production service in that domain, that will guarantee results.

The following paragraphs elaborate on these ideas.

#### **1. VLSI design is a specialized domain**

Reflecting the decomposition of engineering into major categories such as Electrical Engineering and Mechanical Engineering, there may be a tendency to impose a parallel decomposition on design and manufacturing processes:

ME	EE
mechanical design	circuit design
mechanical analysis	electronics analysis
mechanical manufacturing processes	VLSI manufacturing processes

When viewed from this perspective, the state of mechanical design and manufacturing must appear comparatively disorganized and primitive.

But a better perspective is to think of the VLSI world as just another specialized set of design and manufacturing processes – like the those associated with hydraulic systems or DC motors (albeit with a disproportionately large contribution to the nation's GNP). For any specific domain there is much that can be done in terms of design rules, computational tools and infrastructure to expedite the design/manufacturing process. Whether developing such rules, incorporating them into CAD and CAM tools and building an infrastructure to take advantage of them is worthwhile depends on the nature of the process and on economic incentives.

To explore these ideas a bit further let us first consider the VLSI domain, the role and limitations of design rules in it and whether there is anything intrinsic that would prevent analogous developments in other domains.

- *Can the VLSI paradigm be extended to other domains?*

Many of the favorable developments associated with VLSI design and manufacturing stem ultimately from the adoption of design rules. The existence of such rules has made it possible to build a hierarchy of levels of abstraction, allowing designers to work at increasingly abstract levels and isolating them from the details of process engineering.

Therefore, a natural question is to whether design rules inherently work better in the VLSI domain than in others. To be sure, there are some particular advantages in the digital word, some of which have already been articulated by Dan Whitney (e.g., the high gains associated with transistors, combined with digital logic). Other advantages include the (predominantly) two and half dimensional geometry and the reliance upon a family of processes (e.g., etching, deposition, implantation, oxidation, annealing) that leads to many possible recipes. The adoption of a standard CMOS process also affords particular advantages, as others have noted. The upshot is that if the rules are adhered to, the designs are almost certain to work, and with a respectable yield rate.

However, having admitted these advantages, we should note that the arguments currently made against applying VLSI style design rules and standard manufacturing methods to various mechanical and electromechanical domains sound suspiciously similar to those made to Mead and Conway when they first proposed their ideas:

"The unpopularity of such views was almost inevitable. One well-aimed criticism called the approach an over-simplification of the difficulties of device design and held that it overburdened fabrication engineers. Another barb claimed the approach failed to account for basic differences among process technologies." [Marshall et. al. 1981]

Moreover, if we look a bit deeper we see that the concept of scalable design rules is somewhat brittle and subject to tradeoffs and depends heavily on some assumptions about the processes. To begin with, the rules are limited to a set of well defined process recipes and associated device structures (e.g., CMOS, BiCMOS). Rules are largely nonexistent if one attempts to use non-standard devices and processes (for example when making micro-sensors). This is not to say that rules cannot be developed for such applications, only that their current state is essentially the same as it is with many other special domains such as motor design or the design of hydraulic systems – a few expert systems exist.

Moreover even with the standard processes, there is a hierarchy of constraints to contend with as each generation of finer line widths and smaller feature sizes is introduced. Scaling theories can be used, such as constant field and constant voltage, but not everything scales the same way. (For example, if we reduce device dimensions as  $1/S$  then delay time goes as one over  $S$  squared and packing density as  $S$  squared but power density grows as  $S$  cubed) [Meindl 1984] The results can be seen in the debates over what voltage to use for each successive design generation. For example, consider the progression of 1 to 4, 16 (5 volt), 64 (3.3 volt) and 256 (2.5 volt) Mbyte DRAMs [Larrabee and Chatterjee 1991].

Thus far, designers and process engineers have encountered no insurmountable difficulties although there are challenges to overcome and design tricks to develop with each generation of shrinking dimensions (for example, making capacitors as edgewise trenches sunk into the substrate to maintain adequate capacitance).

The point of these examples is that in VLSI design, as in other domains, design rules can be generated. But the rules will embody assumptions about the domain that are only partly true. As process limits are stretched the rules need to be modified, with some effort.

## **2. Is it worthwhile from a design standpoint?**

Whether the effort is worthwhile from a design standpoint depends on how important it is to be able to design large, complex systems from many standard elements.

The ability to combine basic elements while remaining assured of predictable system properties leads to "kit design." Kit design is a great way to manage complexity, composing extremely complex systems from large numbers of well understood components. The requirement is that when the elements are brought together they must interact in completely predictable ways so that the system behavior remains predictable. The utility of kit design depends on the relative importance of managing complexity as compared to the need to minimize other objective functions such as weight, space and power consumption.

Thus, to pick an example at the other extreme of physical scale from VLSI design, power plant design is a domain for which kit design has been successful. Elements such as pumps, heat exchangers, turbines, valves and piping are combined into complex circuits. The approach is successful because the need to minimize real estate is less critical than need to develop and analyze complex systems rapidly.

Moreover, in circuit design there was a time when hackers sought to minimize the number of transistors with clever designs. Similarly, there was a time when software designers often resorted to ingenious segments of assembly code to save a few instructions. Today, with the improving efficiency of compilers and the decreasing cost of RAM this kind of optimization is rarely worthwhile. But in domains such as combustion engine design, a few pounds saved or a one percent improvement in overall thermodynamic efficiency is a big deal and well worth the effort.

Actually, the word "complex" is being used loosely here. Complexity is not measured just in terms of the number of interacting components. As Jim Rinderle of U. Mass Amherst points out, a better measure is "information content," possibly building on the information theoretic measures in David Wilson's thesis [Wilson 1980]. From this standpoint we are likely to find that a new gasoline engine has a complexity much larger than the number of components would suggest.

In light of these considerations, the unsurprising conclusion is that scalable design rules, coupled closely to models of manufacturing processes, can be developed in a variety of domains provided that the limits to their applicability are understood and documented. At the least, design rules can often be applied to a family of products such as motors of various horsepower ratings. Many such systems have been developed. (For example, I recall that when I was machine designer at ALCOA we had something like scalable rules for smelting pot design.) The presence of such rules allows expert systems to be developed that automate much of the routine design and manufacturing planning and make it possible to move rapidly from design to production.

Even if we take a broader class of parts, such as parts made by CNC machining rather than from a particular design domain, if we use parametric features (e.g. per PDES/STEP) and some of the ideas from Group Technology we can obtain a degree of scalability and design reuse. Not surprisingly, the CAD programs that provide for parametric feature-based design are enjoying a rapidly growing market share.

Of course, we also need to make it easy for designers to avail themselves of such tools. To realize the full power of design rules we need an infrastructure of services (perhaps over the Internet) that can work with the resulting designs for analysis and manufacturing prototyping. This leads me to my last topic, which is the motivation from a manufacturing infrastructure.

### **3. Is it worthwhile from a manufacturing standpoint?**

Whether people will be willing to abide by design rules also depends on manufacturing issues. Semiconductor fabrication facilities are incredibly expensive and access to them is a valuable commodity. One of the selling points of MOSIS was the ability to broadcast the rules of the game and have people submit designs in a standard format to have them fabricated with an excellent chance of producing a working artifact.

The same powerful incentive still applies. For example, I recently submitted a couple of microsensor designs to the ARPA-sponsored project at MCNC, despite the presence of a VLSI fabrication facility at Stanford, because of the attractiveness of an inexpensive service using a standard recipe and design rules. Unfortunately, as I and the other participants discovered, the rules



and process were not completely debugged so that many of the prototype devices in the first batch did not work as expected.

If we compare the case of VLSI manufacturing to CNC machining, the picture is entirely different. CNC machining facilities are found in many institutions and in small job shops all over the country. If you offered me a service that would allow me to design machined parts and transmit the designs by e-mail to a central facility would I use it, or would I submit designs via modem or floppy disk to a local job shop, with phone calls to answer questions and iron out details, as I can do now?

Actually, if my design involved intricate geometries, tight tolerances or other features that only a specialized facility could produce with absolute reliability then I would be happy to use a central facility. This is an area in which good process models and process control can play an important role.

In the semiconductor processing world, accurate models of the process physics (e.g., for deposition or ion implantation) have been invaluable in reducing the time needed to develop new, reliable process recipes. Similarly, in process industries such as polymer, aluminum and steel production, accurate process models and tight process control are the norm. Unfortunately, for small batch processes like CNC machining, the ability to predict analogous elements of the process physics (such as relationships among cutting forces, speeds, temperatures and surface finishes) is not as good – partly because the process is so sensitive to local variations in material hardness, friction, and partly because there is less control of materials and processing conditions.

This suggests that good candidates for centralized prototyping and manufacturing services are processes with expensive facilities and well developed process modeling and control for reliable results. Examples might include services for thermoplastic composites and injection molding (including tool design). Tools and libraries for high-level design, analysis and process planning would have to be part of the package.

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### **3.4.6. POSITION PAPER BY RICHARD F. RIESENFELD**

#### **CAD: ISSUES IN VLSI AND MECHANICAL DESIGN**

**Richard F. Riesenfeld**

**University of Utah**

**April 1994**

Many knowledgeable individuals have expressed viewpoints on the comparative aspects of automation in VLSI and MCAD, e.g., the well-structured background notes and contributed statements for use in this upcoming NSF workshop. In an effort to make my remarks more succinct, I will try to focus on some points about which I feel most strongly and where I feel that I may have some additional perspective. For balance, I will rely on many distinguished colleagues to cover equally important points in areas closer to their expertise like analysis, systems simulation, product simulation, constraints, and interface handling.

In terms of overview, let us observe that VLSI is distinctly and properly regarded as an enormously successful undertaking. It has been developed with substantial funding, close coordination, and programmatic leadership. With the advance of the technology, a closely knit, highly cooperative community has developed. The esprit de corps, the responsibility of the community in shouldering the overall advancement of the technology with coordinated and compatible tools, seems an extraordinary situation that accounts for some of the success in VLSI. The name Robert Kahn is commonly cited in discussions with people involved in analyzing the forces that brought about this extraordinary success. He represented a long term sustained commitment of both intellectual and organizational leadership in combination with substantial research funding support. Such cohesiveness and individual leadership has not been paralleled in the world of MCAD. Nor have I found in ME the corresponding atmosphere that might lead to similar cooperative efforts as exists in VLSI. MCAD researchers are a much looser confederacy of highly talented leaders heading largely disparate projects that generate incompatible tools.

Partly because of this fragmented history of MCAD, integration of essential modular capabilities remains important research area in MCAD. There may be exquisite solutions that work on highly specialized models but are not applicable as part of an integrated solution. Integration may actually require developing new solutions to apply to new models that lend themselves to proper integration. For example, models for manufacturing and geometric modeling are quite distinct in their contents, requirements, and purposes.

This can become a politically difficult research area because, to a casual observer, it may appear that one may have not substantially advanced a narrow specialty, a component area, but merely brought a similar looking solution to work in an integrated environment. Undertaking such tasks has its obvious professional risks.

While I agree with many of the points of comparison, both in the similarities and differences between VLSI and MCAD, I join with the assessment that the M-problem is substantially more complicated for many of the reasons that have been expressed and elucidated. MCAD is a fundamentally 3D problem and we have substantially less understanding and capability for working in a genuinely three-dimensional space than is commonly appreciated. That is, much of the 3D interaction which is observed around us has to do with inserting a 2D construction in a 3D environment or in inserting very simple shapes in a 3D environment. We have rather little ability to deal with complex shapes in a full 3D environment. That problem is a significant distinguishing characteristics between VLSI CAD and MCAD.

It has been noted that the functions of the design elements in mechanical engineering often perform-purpose functions. This makes the analysis of the process of mechanical design and manufacture far more complicated. The decomposition may not layer itself into disjoint levels of functions and abstractions. Others have provided very illustrative examples of this.

Moreover, the native language of mechanical engineering talks more about the nature of the composition of the design elements rather than the function or the intent. For example, VLSI designers tend to talk about memory, communications buses, CPUs, IO interfaces, and the like. In contrast, mechanical engineers talk about slots, holes, pins, bosses, pockets, beams and columns. These names do not reveal much on the nature of the design function that these elements serve. There is probably room for a lexicon that describes more fully the function and the design intent associated with the introduction of such a design element.

MCAD poorly supports the early stages of design. There is very poor support of the natural flow and refinement of ideas from the conceptual through the preliminary to the detailed design phases. Historically MCAD support for design began at the detail level. Much efficiency could be gained through providing support in the much earlier phases and having a continuous flow of these models through the typical three stages of design.

Traditionally, MCAD has not been concerned with manufacturing or what I call the general process planning problem, which includes stock choice, fixture specification, visibility and accessibility considerations, optimal rough and finish manufacturing, and many of the other details that go into realizing the designed part. This is likely to change. To achieve desired levels of automation and effectiveness, I believe that in MCAD, one will be forced to consider process planning. The manufacturing process is not a fixed backend process that can be automatically applied so long as there was general adherence to obeying proper design rules. The situation is much less structured in ME and much more complicated.

Furthermore, there are levels of manufacturing that pertain. For example, a molded product may get realized from a three stage manufacturing sequence. It may start with a 5-axis milling process to define an electrode for a "Sinking" EDM machine. Then the electrodes could be used to "sink" into hard metal to develop mold parts. Then, finally, the mold parts might be assembled and used to make a mold. This is fairly complicated in that the designer has to worry about primary, secondary, and tertiary stages of manufacturing, that is, if he is considering the manufacturing issues during the design process.

It is important to bear in mind in that the manufacturing process changes in a highly significant way with the scale of production. This further means that it is hard to develop automatically a process plan for a small number of parts, one or two say, that then scales to a production process which may make several thousand or several million. In order to achieve a degree of automation in the process planning, one has to flexibly glide among the processes which support manufacturing one and two parts and redirect that to a process which defines a larger number of manufactured parts. That is a very significant challenge. The same design description may not support process plans suitable for both small and larger lot runs.

There is no general neutral design or manufacturing language, although recently there have emerged serious efforts in this direction. In fact, there is some emerging design and manufacturing vocabulary that is feature based. Unfortunately, the design and manufacturing features do not match up exactly and there is a significant research issue of connecting the two in a coherent and useful way.

At the more accepted level, feature descriptions tend to be at a relatively low level. With this auspicious beginning, it is a clear next step to try to raise the level of abstraction and extent of this feature approach, to raise the power of this approach.

While layer manufacturing technologies are very promising in eliminating some of the complexities associated with defining a traditional process plan for manufactured parts, they do introduce their own complexities as well. There are other issues that have to be supplied in order to effectively use layer technologies, and these new technologies often do not provide products made out of the appropriate engineering materials. So while this is a very promising area, it is not yet a panacea to the general process planning problem. There are many cases in which a state-of-the-art approach can produce a traditional prototype more rapidly in a useful engineering material that a layered technology requires for a non-engineering material prototype. On the other hand, some developments in this area are rather exciting and will doubtless change the world of ME design and manufacture.

There are other major matters in MCAD that are necessary for support CAM. Fixturing is often a problem of equal or greater challenge than the actual artifact of design. It is a next major area that deserves considerable focus. We have not discussed major issues of post machining, like CMM for quality monitoring, nor have we discussed reverse engineering, and design reuse.

Tolerancing is a major topic and a formidable challenge. It is much more difficult in a 3D world. Without developing this point, I only would like to emphasize that it is an important area with difficult problems. The area of tolerancing is not sufficiently advanced for the levels of automation that we seek.

I would like to conclude in a more upbeat note. Namely, it is very encouraging to see the progress that is occurring and the rapid momentum that is gathering. There are examples of tremendous progress and an inexorable speedup that would have been hard to imagine only five years ago. If not gracefully then at least methodically the revolution IS occurring. MCAD is a more difficult problem domain. It is a problem domain that can borrow abstract lessons and principles concerning approach in drawing on the success of the VLSI community, but is not a problem domain where wholesale adoption of VLSI techniques and experiences can be blindly applied. The VLSI success certainly should be a source of enormous inspiration.

Further, I note that the progress in MCAD is taking place on two important fronts. We are greatly advancing the efficiency with which we can rapidly produce prototypes from conventional manufacturing processes. We are also exploring unconventional layer technologies and other new processes to gain advantages in brand new and exciting areas. The assembly of people at this workshop is an indication of the level of talent and leadership that this problem has attracted.

In becoming a "Grand Challenge Area," Manufacturing may also enhance the academic respectability of computing research in this domain. This is a problem that VLSI researchers seemed to avoid, maybe because of the close relationship of EE and CS as sister disciplines. This is important in opening up the area to younger researchers who may become subject to rather traditional professional evaluations.

### 3.4.7. POSITION PAPER BY JOSEPH BEAMAN

#### **VLSI AND NEW PARADIGMS FOR MECHANICAL COMPONENT MANUFACTURE**

**Joe Beaman**  
**University of Texas**  
**April 25, 1994**

Although at first glance, the relation between VLSI design and fabrication and mechanical component manufacture seems weak. I believe that some of the process techniques used in VLSI warrant further study. Especially in regard to Solid Freeform Fabrication a layer-wise manufacturing technique.

Since manufacturing is such a broad topic, I wish to limit my comments to component manufacture which might occur in mechanical or electromechanical products. This also seems to be the spirit of the workshop paper by Hilibrand and Chern. If we temporarily limit ourselves to just electronics, there are numerous discussions of discrete component manufacture versus VLSI manufacture. A typical comparison is given below.

	DESIGN		ASSEMBLY		PRODUCTION COST	
					Volume	
	TIME	COST	TIME	COST	TIME	COST
Discrete Components	Med	Med	Long	High	Med	High
Standard IC Packages	Short	Low	Med	Med	Low	Med
Custom IC Packages	Long	High	Short	Low	Low	High

This chart indicates that systems with electronic components cost less and take less time to fabricate than discrete components if standard IC packages can be used, and only for high volume production does a custom VLSI package make sense. Unfortunately, most mechanical and electromechanical components require the functionality and complexity much beyond that of even a custom IC and certainly more than a standard IC. In general, there are many component types and multiple functions required by mechanical products. The reasons for this are ably expressed in the papers by Whitney and Sequin.

Although much can be learned from any success like VLSI manufacturing, at first glance, there does not seem to be a strong correlation between mechanical component manufacture and the VLSI paradigm. But, rather than focusing on the differences between VLSI products and mechanical and electromechanical products, let us consider one compatibility (There are probably others). Mechanical products often require and VLSI processes can produce incredibly complex structures. Although in VLSI, unlike mechanical structures, the same structures are repeated many times, this is not a requirement of the process. VLSI process techniques provide this complexity by selective addition and subtraction of material along one dimension by lithography, etching, diffusion, implantation, etc. This is in sharp contrast to standard methods to fabricate mechanical components which include removal processes like machining, forming processes like forging, and joining processes like welding. These processes typically occur in multiple dimensions and therefore require special tools, dies, fixtures, and tool path planning to create a complex object with only incremental complexity added during each set up.

#### **Solid Freeform Fabrication**

Today, several new technologies are capable of producing complex freeform solid objects directly from a computer model with out part-specific tooling or knowledge. Like VLSI manufacture, they are for the most part layer-wise additive methods. Unlike VLSI, they are not presently targeted at high volume manufacture, but rather at rapid creation of models, prototypes, patterns, tooling, and limited run manufacture of mechanical components. These technologies have been termed rapid prototyping, desk top manufacturing, and solid freeform fabrication. By building parts up along one axis, requirements for fixtures to hold objects can be greatly relieved. While a part is being constructed,

sacrificial support structures can be simultaneously built, support material added, or, even better, the nonprocessed material acts implicitly to constrain the part during fabrication.

## **VLSI Process Technology and SFF**

The benefits of making complex parts in a single operation without part specific tooling or human intervention are obvious, but these benefits do not come without cost. In many ways, the tenets of standard manufacturing processes are changed in freeform fabrication techniques. Rather than starting with structurally sound material and then removing material in order to obtain geometric complexity as in standard machining, freeform fabrication incorporates geometric complexity in concert with structural properties by material addition. The manufacturing and material science required to optimally produce mechanical parts by additive layer-wise methods is in its infancy. A logical question then arises: Do VLSI layer-wise processing techniques offer solutions to SFF processing problems? In partial answer to this question, potential areas for VLSI/SFF research include:

1. Effective integration of electronic and mechanical functions in a single manufacturing process.
2. Layer by layer quality control.
3. Design rules for SFF.
4. Benefits of selective material removal in SFF processes.
5. Layer deposition techniques.
6. Benefits of selective multiple-material addition.
7. Selective CVD processes.
8. Process control techniques
9. Management of complexity in design and manufacture.

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### **3.4.8. POSITION PAPER BY DANIEL SIEWIOREK**

#### **HIERARCHICAL ABSTRACTION, VLSI, AND MANUFACTURING**

**Daniel Siewiorek**

**Carnegie Mellon University**

**April 21, 1994**

#### **BACKGROUND**

Engineering design of complex systems is based upon a series of abstractions that are hierarchically organized. Each layer in the hierarchy uses components to construct subsystems which, in turn, become the components for the next higher level in the hierarchy. Components are typically defined by at least two separate perspectives: behavior and structure. Behavior can include mechanical, electrical, logical, etc. Physical artifacts are realized by manufacturing at each level in the hierarchy. Different manufacturing paradigms support one or more levels in the hierarchy. Thus more than one manufacturing paradigm will typically be used in a single artifact. Conversely, no single manufacturing paradigm can be used for all artifacts in one domain. The key is to determine matches between the properties of the artifact and the manufacturing paradigm.

Cars, airplanes, computers, and even cities follow the hierarchically structured plan. The introduction of abstractions allows for the more efficient handling of complexity at the cost of introducing inefficiencies. Interchangability of components and design reuse depend upon the rigor with which the interfaces between the hierarchical levels are defined. In other words, by giving up some freedom of expression, designers can more rapidly design and fabricate more complex systems.

For example, cars have a number of subsystems: engine, power train, suspension, steering, etc. Some of these, such as engines, become components which are used in many different car models. When styling or other issues become important, such as in tail lights, common components only appear at a relatively low level, such as light bulbs. All the hierarchical levels in-between have to be uniquely designed and manufactured.

Design and manufacturing can be simplified through the added inefficiencies of abstraction and standardization. For example IBM uses Level Sensitive Scan Design (LSSD) in their logic chips to simplify test set generation and testing of the final system after manufacturing or in the field. LSSD has been used in mainframe computers and is incorporated in the new Power PC chip line. LSSD costs about 20% in area and up to 10% in performance. The discipline of using LSSD has been accepted in return for simplifying systems validation and checkout.

#### **VLSI AND MECHANICAL SYSTEMS**

There is a mismatch between traditional manufacturing and VLSI fabrication techniques. Thus it is not likely that the VLSI experience can be transferred in whole without modification to mechanical systems.

VLSI does not decrease the fabrication time for an electronic part. In fact it may take six weeks to produce a chip. But the manufacturing effort per chip is small due to the simultaneous, parallel fabrication of tens of wafers containing hundreds of chips. Note that some traditionally manufactured components have been redesigned to meet this criteria such as sensor arrays and power electronics.

VLSI also enjoys scaling of the components. Components can be made smaller and smaller as the fabrication technology improves. Scaling has been used in non-digital subsystems such as displays (to improve resolution) and transducers (to improve dimensions/accuracy). Systems whose physical loads do not scale (such as the transmission of a car) can not take advantage of the improvement in fabrication technology. Of course load can be distributed across parallel components which in turn

may scale trading parallelism for size. Parallelism has been used many times to reduce size (I saw a 40-wheel truck this past weekend!).

VLSI has enjoyed mass markets where-as many mechanical systems are produced in smaller batches (except for cars). Mass production enables more expensive fabrication facilities.

It should be noted that not all electronics is fabricated by VLSI. Analog devices and microwave components use other techniques. But as the cost of digital electronics decreases due to the large economies of scale, designers find ways of converting formerly analog processes to digital form. Any inefficiencies are swamped out by economics of scale.

Note also that electronic systems are coupled. Power systems for example allow bi-directional flow. Parasitic properties become more important as device dimensions shrink. Wires are now all treated as distributed transmission lines due to the high clock frequencies.

## **WHERE WE SHOULD BE LOOKING**

Layered manufacturing has many advantages. We should be exploring the portions of the physical world that admit to layered manufacturing techniques. Sometimes new manufacturing techniques are required to provide advantages that can not be provided by existing techniques. Single metallurgical crystals enables gas turbine blades to run hotter and longer than previously. Poured concrete enabled the fabrication of buildings in "layers" rather than the more traditional frame and covering "approach".

One area that layered manufacturing holds high promise for is electro-mechanical systems. Consider electric motors in the car of the future. The motors will be used for door locks, windows, windshield wipers, etc. They will receive commands from a digital vehicle network. A network interface and small computer would control the behavior of the motor. The electronics could be built up in conformal layers directly into the housing of the motor. These systems are typically relatively low power consumers but make up a substantial portion of the cost of the larger artifact. More than half the cost of buildings and airplanes are made up of the electronic/electrical cost. As artifacts become even more "information rich" there will be even more opportunities to include electronics into what historically have been relatively passive components.

## **SUMMARY**

The VLSI experience will probably not transfer over directly to mechanical design. Likewise, one manufacturing paradigm will not be applicable to all mechanical systems. However we should distill the essential lessons from the VLSI experience and see how they can be applied in new manufacturing processes and information rich components.



### 3.4.9. POSITION PAPER BY DANIEL E. WHITNEY

#### **SOME DIFFERENCES BETWEEN VLSI AND MECHANICAL DESIGN**

**Daniel E Whitney**  
**Mass. Institute of Technology**  
**April 28, 1994**

I think there are fundamental reasons why VLSI design is different from, and substantially easier than, mechanical design, and I think the differences will persist. My conclusions are summarized in Table 1 and the reasoning is sketched below. An essential feature of the argument is to distinguish carefully between parts or components on the one hand and products or systems on the other. The Table displays this distinction.

<b>ISSUE</b>	<b>VLSI</b>	<b>Mechanical Systems</b>
<b>Component Design and Verification</b>	Model-driven design, single function components; design based on rules once huge effort to verify single elements is done; few component types needed	Multi-function design with weak or single-function models; components verified individually, repeatedly, exhaustively; many component types needed
<b>Component Behavior</b>	The same in systems as in isolation; dominated by logic, described by mathematics; design errors do not destroy the system	Different in systems than in isolation; dominated by power, approximated by mathematics, subject to system- and life threatening side effects
<b>System Design and Verification</b>	Follows rules of logic, can be proven correct; system design separable from component design, simulations cover all significant behaviors; main system functions accomplished by standard elements; building block approach exploited and probably unavoidable	Logic captures a tiny fraction of behavior; system design inseparable from component design; cannot be proven correct; large design effort devoted to side effects; component behavior changes when hooked into systems; building block design approach unavailable, wasteful
<b>System Behavior</b>	Described by logical union of component behaviors; main function dominates	No top level description exists; union of component behaviors irrelevant; off-nominal behaviors may dominate

Table 1. Summary of Differences Between VLSI and Mechanical Design

1. Mechanical systems carry significant power, from kilowatts to gigawatts. A characteristic of all engineering systems is that the main functions are accompanied by side effects or off-nominal behaviors. In VLSI, the main function consists of switching between 0 and 5 (or 3 or 2.4) volts, and side effects include capacitance, heat, wave reflections, and crosstalk. In mechanical systems typical side effects include imbalance of rotating elements, crack growth, fatigue, vibration, friction, wear, heat, and corrosion. The most dangerous of mechanical systems' side effects occur at power levels

comparable to the power in the main function. In general there is no way to "design out" these side effects. A VLSI system will interpret anything between 0 and 0.5 volts as 0, or between 4.5 and 5 volts as 5. There is no mechanical system of interest that operates with 10% tolerances. A jet engine rotor must be balanced to within 10-2% or better or else it will simply explode. Multiple side effects at high power levels are a fundamental characteristic of mechanical systems.

One result of this fact is that mechanical system designers often spend more time anticipating and mitigating a wide array of side effects than they do assembling and satisfying the system's main functions. Gaps in engineering knowledge are mainly responsible for the consequent difficulty. This dilution of design focus is one reason why mechanical systems require so much design effort for apparently so little complexity of output. Correct accounting of "complexity of output" must include the side effects.

2. By contrast, VLSI systems are signal processors. Their operating power level is very low. Few if any mechanical signal processors exist any more (dial readouts on gas meters are about the only example). Since they process tiny amounts of power and because only the logical implications of this power matter (the effect of the equivalence of digital logic and Boolean algebra), VLSI circuit elements can be connected together in building-block fashion. The elements do not back-load each other. (If fanout limits are reached, amplifiers can be inserted at some cost in space, power, and signal propagation time. But this is not fundamental.)

An enormously important and fundamental consequence is that a VLSI element's behavior is essentially unchanged almost no matter how it is hooked to other elements or how many it is hooked to. That is, once the behavior of an element is understood, its behavior can be depended on to remain unchanged when it is placed into a system regardless of that system's complexity. The result of this is that VLSI design can proceed in two essentially independent stages, of which the first (design of components) shares most of its features with mechanical design while only the second (design of systems) is different:

Stage 1: Logic elements are designed and processes are designed to make them. This requires enormous effort involving lithography, metallurgy, chemistry, electric field analysis, purification of fluids and gases, and training of people, to name a few.

Stage 2. Once this difficult step is done, the results can be expressed as design rules and the product designers can use the elements as described above. The problems in Stage 2 are almost completely logical or reducible to mathematical description because the systems are signal processors or logic implementors. Designers can focus their efforts on system issues like floor planning, timing, basic architecture, system logic, and so on. Furthermore, due to the mathematical nature of VLSI digital logic and its long understood relation to Boolean algebra, the performance of VLSI systems can often be proven correct, not simply simulated to test correctness. But even the ability to simulate to correctness is unavailable to mechanical system designers. Why is this so?

3. An important reason why is that mechanical components themselves are fundamentally different from VLSI components. Mechanical components perform multiple functions, and logic is usually not one of them. Multi-functions are partly due to basic physics (rotating elements transmit shear loads *and* store rotational energy; both are useful as well as unavoidable) and partly due to design economy. VLSI elements perform exactly one function, namely logic. They do not have to support loads, damp vibrations, contain liquids, rotate, slide, or act as fasteners or locators for other elements. Designers can build up systems bit by bit, adding elements as functions are required. The absence of back-loading aids this process. Design economy dominates mechanical design: if one element were selected for each identified function, such systems would inevitably be too big, too heavy, or too wasteful of energy. For example, the outer case of an automatic transmission for a car carries drive load, contains fluids, maintains geometric positioning for multitudes of internal gears, shafts, and clutches, and provides the base for the output drive shafts and suspension system.

The situations where this characterization is invalid provide valuable cautions: VLSI that stretches the state of the art encounters severe system-level difficulties. The separation described here may not be dependable in the future as processing speeds and chip sizes increase. Timing and heat

problems are early harbingers. A 33 Mhz 486 is in fact a 40 Mhz 486 that did not pass the 40 Mhz test. This flavor of this story is distinctly non-digital. Not only is there no other way to design such a case but the designers would not have it any other way. Mechanical designers depend on the multi-function nature of their parts to obtain efficient designs. (Building block designs are inevitably either breadboards or kludges.) But this forces them to design components over and over to tailor them to the current need, again sapping the effort that should be devoted to system design. VLSI designers, by contrast, depend on the single function nature of their components to survive the logical complexity challenges of their designs. One can observe the consequences of this fundamental difference by observing that in VLSI the "main function carriers" are standard proven library elements while in mechanical systems only support elements like fasteners are proven library elements; everything else is designed to suit.

VLSI elements don't back load each other because they maintain a huge ratio of output impedance to input impedance, perhaps 6 or 7 orders of magnitude. If we tried to obtain such a ratio between say a turbine and a propeller, the turbine would be the size of a house and the propeller the size of a muffin fan. No one will build such a system. Instead, mechanical system designers must always match impedances and accept back-loading.

4. The fundamental consequence of back-loading is that mechanical elements hooked into systems no longer behave the way they did in isolation. (Transmissions are always tested with a dynamometer applying a load; so are engines.) And these elements are more complex than VLSI elements due to their multi-function behavior. This makes them harder to understand even in isolation, much less in their new role as part of systems. VLSI elements are in some sense the creations of their designers and can be tailored to perform their function, which is easy in principle to understand. Mechanical elements are not completely free creations of their designers unless, like car fenders, they carry no loads or transmit no power. The existence of multiple behaviors means that no analysis based on a single physical phenomenon will suffice to describe the element's behavior; engineering knowledge is simply not that far advanced, and multi-behavior simulations similarly are lacking. Even single-behavior simulations are poor approximations, especially in the all-important arena of side effects like fatigue, crack growth, and corrosion, where the designers really worry. In these areas, geometric details too small to model or even detect are conclusive in determining if (or when, since many are inevitable) the effect will occur. And when component models are lacking, there is a worse lack of system models and verification methods.

Thus a number of success factors in VLSI may be blocked from application in mechanical design. For example:

- Re-use of library elements may be inapplicable because inefficient designs would result. "Good" mechanical design usually does not reuse components. Many horror stories are available!

- Direct conversion of specifications to system design is unlikely to be applicable because logic is the language of VLSI's specifications and system description, and this language is not only conclusive and provably correct but it captures all the behaviors that the system will exhibit once the component design rules are known. In mechanical systems there is no specification language. Instead we have Quality Function Deployment or other semi-mystical attempts to convert what the customer wants into hard engineering specifications. It is premature to say that there will never be a mechanical spec language, but mechanical systems are not primarily driven by logic; instead they are driven by power flows among many physical phenomena. The mathematical representations we have here apply to single phenomena: stress, fluids, electro-magnetic fields, dynamics, but these are not integrated into one set of equations except in the case of Bond Graphs which imply a building -block approach, which has its own disadvantages.

- There may not in fact be a "clean separation between VLSI manufacturing and VLSI design" since the VLSI components must be designed as verifiably manufacturable. But there is a compensating separation between VLSI component design and VLSI system design. Since this separation does not exist in efficient mechanical designs, this valuable property may be blocked from exploitation in the mechanical world.

- The reason why "an enormous variety of VLSI products can be built" from the same process is that the variety is embodied at the system level. At the component level, only one item can be made by each process. VLSI escapes the consequences of the process-dependence of components because VLSI systems can be designed independently of component design. On the mechanical side, this separation does not exist, indicating why "a great variety of mechanical products" can't be made by the same process. The process-dependence of components has inevitable linkages to the whole product system.

- "Process-constrained design" can indeed be practiced in mechanical systems and routinely is. That's how we decide if a particular machine is suitable: can it deliver the tolerances needed, for example? If not, the design may have to be changed. But many factors contribute to tolerance capability, and it is a random variable, due in large part to the power needed to remove metal efficiently. So the process constraints are much harder to determine and the effort is not completely rewarded.

- "Tool hierarchies" can be used in VLSI because at the system level the information is entirely logical and connective, and the tools in question are used in system-level design. This information is transformed and augmented from stage to stage in the design process but its essential logical/connective identity is preserved all the way to the masks. This is not possible in mechanical systems, where the abstractions are not logical homologues (much less homomorphs) of the embodiments and likely never will be. Instead, there is tremendous conversion needed, with enormous additional information required at each stage. A stick figure diagram of an automatic transmission captures only the ~ of the gear arrangements and shifting strategy. It fails totally to capture torques, deflections, heat (a basic property, not a mere side effect since huge energy is released during shifts, just like the heat that emerges when logic gates switch, and for exactly the same reason!), wear, noise, shifting smoothness, and so on, all of which are essential behaviors.

### 3.4.10. POSITION PAPER BY ERIK ANTONSSON

#### COMPARISON OF VLSI DESIGN AND MECHANICAL DESIGN

Erik Antonsson

Calif. Institute of Technology

April 21, 1994

The NSF Workshop paper by J. Hilibrand and B. Chern raises many interesting and provocative points of comparison between VLSI design and Mechanical design. The paper suggests a challenge to the Mechanical design community to adopt (and adapt) the VLSI design paradigm.

The salient features of the VLSI design process that Mechanical design might aspire to are:

1. Form and Function can be considered separately. This creates an environment where the designer can *first* consider the function that is desired of her design, then separately consider how that function will be implemented in hardware.
2. A set of standardized design rules exist that permit the form and function decomposition. The design rules have this capability because they are *conservative* and permit the designer to ignore many difficult, complex, and potentially troublesome effects. Most important is that these design rules permit the designer to consider the flow of electrons as a scalar quantity, and to ignore any of the complications of 3D electromagnetic effects, or crosstalk, or non-linearities, etc.
3. The manufacturing process(es) have been standardized.

I believe that this is a valuable avenue for discussion, and future research, but I also believe that the discussion can and should be widened somewhat. There exists a spectrum of formal design methods in several domains. VLSI design is perhaps the most formal but other areas have found some formality too. Perhaps the closest to VLSI design is Chemical Process design. Here the designers have CAD tools and methods that permit them to specify a high-level function and the details of the implementation of that function are left to the program, or at the very least, can be wholly considered separately.

Software design is next in formality, in that many of the lowest level functions that formerly required assembly language programming are now handled automatically by compilers. For example, a `printf` statement in C is a moderately high-level functional request by the software designer. The details of how that `printf` function is implemented are entirely left to the compiler (or the run-time library), and in any event can be wholly considered separately. Unfortunately higher level software design tasks remain largely informal.

I think that our discussion can be augmented by including a consideration of these other areas, as a way of extracting the general aspects of these design domains that are amenable to formalization, and those that present difficulties. There may be other areas that should be included in our discussion, for example there are moderately well developed design rules for injection molding and sheet metal design.

My own view of the distinction between Mechanical design and the other areas for which some formalisms have been developed is as follows:

1. Mechanical design must necessarily include 3-dimensional vector quantities (e.g., force, velocity, etc.), at least, and many times must include tensor quantities (e.g., stress, deflection, etc.). Material properties are usually directional, and processing during manufacture affects these properties and their directionality. The aspects of design that have been formalized in the other areas briefly mentioned above all treat the quantities that the designs process as scalar (electrons in VLSI, mass and heat flow in chemical process design, information in software). The intrinsically higher dimensionality of the design space in Mechanical design complicates the design process. As a further example, most mechanical components do not exhibit the same function independent of orientation or location. A bearing, for example, will exhibit the desired function if it is oriented parallel to its shaft, and is located co-axially with the shaft. If either the bearings orientation or location is changed, its function will change dramatically.

2. As Dan Whitney eloquently pointed out, component interaction is either minimized or eliminated in the design domains that have been amenable to formalization, but component interaction is a necessary aspect of mechanical design.
3. The previous point can be echoed for function sharing. Design domains that have been formalized have minimized or eliminated function sharing, creating a design environment where each element in the design has one and only one function. Successful mechanical designs exhibit a high degree of function sharing. Dan's example of a mechanical power transmission case performing many important functions is an example that I have used myself many times.
4. VLSI and Chemical process design (and perhaps software) have a limited number of standard components to select from. Design complexity and richness comes from employing a large number of these components in increasingly complex system designs. In contrast, Mechanical design has an arguably infinite number of components that can be employed. The trend in Mechanical design is, in fact, away from standardized components. For example, if you look at a motorcycle (a mechanical design that is not clothed in stylistic body work that hides the mechanical systems), motorcycles designed and built 30 (or more) years ago are largely comprised of components that could be purchased at a well stocked hardware store. A contemporary motorcycle has very few of these standard mechanical components, in favor of specially designed components that share function and reduce cost and weight. This trend has been more or less continuous since 1900. The same trend can be seen in automobiles, toasters, typewriters, etc.
5. I will end my list by vigorously seconding Dan Whitney's observation about the importance of unmodeled or unmodelable effects in Mechanical design. Mechanical designers are constantly faced with having to design devices to operate under conditions and in the presence of effects that we do not yet understand very well, for example: friction, fracture, fatigue, corrosion, etc. It is hard to imagine being able to successfully develop a formal design process or even sensible design rules in this environment of uncertainty.

My enumeration above seems a clear call for pessimism, however, I remain quite strongly optimistic about the prospect for development of formal methods for Mechanical design. The recent history in the Mechanical design research community is cause for this optimism, including Stiny's Shape Grammars (now increasingly extended to the functional domain), Ward and Seering's Mechanical Compiler, Simulated annealing and genetic algorithm design methods developed by Cagan and Jakiela and many others, Tomiyama's qualitative physics methods, and many other developments in Mechanical design research too numerous to mention here. Progress has been made by learning from the successes (and failures) in other areas, and by tackling only a (small) portion of the Mechanical design process at a time.

### **3.4.11. POSITION PAPER BY HERBERT VOELCKER**

#### **NEW PARADIGMS FOR MECHANICAL DESIGN & MANUFACTURING?**

**Herbert Voelcker**

**Cornell University**

**April 24, 1994**

#### **INTRODUCTION**

This workshop's goal is to seek new paradigms for mechanical design and manufacturing through the study of VLSI design and manufacturing technology. It is worth noting that this workshop is the latest in a 9- or 10-year series of meetings, workshops, and initiatives aimed at a 'Mechanical MOSIS'. Throughout this period the 'pro' arguments for mechanical analogs of VLSI techniques and processes have not been compelling enough to justify proof-of-concept projects, and in fact most of the arguments have been muddy and often naive.

In 1985 I wanted to be a believer, but by about 1990 I had become a strong skeptic – for reasons given below. Thus I don't expect this workshop to identify useful 'mechanical' paradigms from VLSI (I'll be pleased if proved wrong!), but we can do useful work simply by dispatching the fuzziness surrounding the topic. If we go further and probe the fundamental differences between digital-electronic and mechanical design and manufacturing, we might just possibly find openings for advances in unexpected directions.

#### **DIGITAL-ELECTRONIC PRODUCTS AND VLSI**

I believe that the efficacy of VLSI derives mainly from the character of digital electronics, with the 2.5-D layered VLSI manufacturing process being at most a secondary source. Specifically (and with some over-simplification), digital electronic products

- are systematic combinations of very large numbers of elements from a very small set of functional primitives, e.g. NOR and index/transfer;
- derive their variety, functionalism, and complexity from discrete combinatorics;
- can be designed (at least in principle) by systematic mathematical recursion;
- are largely independent of spatial geometry and 'the tyranny of continua' (I seem to recall that electronic devices must correspond to topological 1-complexes embeddable in  $E^3$ );
- are largely divorced from the concerns of classical physics – work, mass, stress, and the like – and, despite entropy analogies, do no work (apart from unwanted conversion of electricity to heat) recognized as such by physicists.

The 2.5-D VLSI fabrication process strikes me as discretionary – one of presumably several ways in which one could embed a topological complex in a Euclidean space – but clearly it has proven to be a serendipitous choice.

#### **MECHANICAL PRODUCTS**

All mechanical products can be described, analyzed, and designed in terms of energy exchange, although that is not always the most effective way to do business.

- Mechanical products cater for several forms of energy, often simultaneously:
  - thermal energy, as in heat exchangers and refrigerators;
  - fluid-dynamical energy, as in gas turbines;
  - deformational energy – elastic and plastic, both traceable to the micromechanics of materials;
  - electric and magnetic energy, as in power switch gear and large motors;
  - ... and others.

Mechanical products are necessarily spatially distributed, and their forms are chosen to channel and limit energy concentrations. (Why *necessarily* spatially distributed? Perhaps the most fundamental reason is to limit the spatial density of energy within the product.)

- There are no known sets of 'functional primitives' for mechanics that are in any sense analogous to the Boolean and sequential-logic primitives of digital electronics. (The low-order kinematic pairs – two-element joints with one or two relative degrees of freedom – have been studied as possible primitives, but they generally do not qualify for reasons I shall not delineate here.)
- Mechanical products are quasi-combinatorial or 'modular' only at intermediate and higher system levels. The crossover point for modularity seems to be at significant-part counts of  $O(10) - O(100)$ . (Washers, standard fasteners, and the like are not considered 'significant'.) For example: an industrial compressor or a household washing machine has  $O(100)$  significant parts that are custom designed as an aggregate, and set the character of the product. Subsystems – pumps, motors, transmissions, controllers, ... – are attached, each having  $O(10-100)$  significant parts designed as an aggregate, and each being either a custom design or, more usually, a catalog item. (There are many exceptions, because the variety of mechanical goods is enormous. Large fabricated structures such as commercial jet aircraft probably contain  $O(1000)$  significant parts, but there are many duplicates in the set.)

## MECHANICAL DESIGN

Mechanical design is significantly combinatorial in the early, top-down phases when major subsystem decisions are being made and the product configuration is being set. As design becomes more detailed and falls below the  $O(10-100)$  part-count threshold, modularity is gradually abandoned and function-sharing becomes the guiding principle. Shared-function designs are the antithesis of modular designs, and the importance of function sharing sets mechanical design apart from software design and modern electronic design (but not from old-fashioned electronic design; oldsters may recall that a single 6SN7 often served as an i-f buffer, audio detector, and audio amplifier).

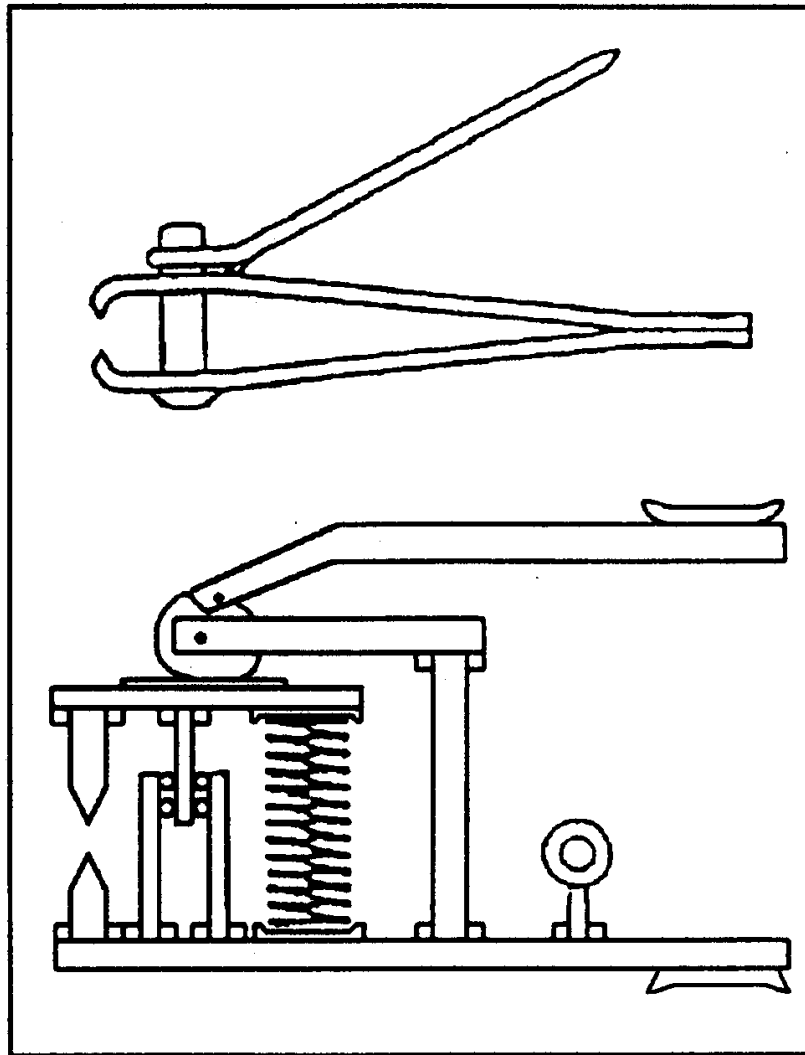
The case for function sharing rests on efficiency – reduced weight, lower part count, fewer assembly operations – although these advantages sometimes impose higher tooling costs. Karl Ulrich's elegant example [Ulrich 88] in Figure 1 should make the point without further words from me. (The shared-function design is at the top in Fig. 1, and the modular design is at the bottom.)

## AN ABSTRACT VIEW OF DESIGN

The generic functional specification in digital electronics is (to oversimplify a bit) boolean and sequential expressions: discrete, often recursive, divorced from geometry and any notion of mathematical continuity. Such specifications can be decomposed hierarchically into trees with primitive-operation nodes, and thus implementation design merely requires repeated physical implementation of a few simple logical types, arranged in a manner that enables interconnection. The entire process is discrete if discrete primitive elements (transistors, resistors, etc.) are used. With a



VLSI implementation, discrete elements must be mapped onto a continuous medium, thus effecting a 'discretization' or partitioning of the medium. The fineness of the partitioning apparently is limited by the inter-cell crosstalk.



**Figure 3.4.11.1 - Shared-function design**

In mechanical design, a functional specification often amounts to a partial definition of an initial- or boundary-value problem over a continuous field. The character of the field is set by the constitutive equations for the energetic phenomenon of interest, e.g. Laplacian for heat transfer, Navier-Stokes for fluid dynamical problems, and so forth. The design goal is to specify the domain, which at the single part level means the 'shape' of the spatial region over which boundary conditions are to be met and internal constraints optimized. At higher levels in the design, the goal is partitioning of the domain into subdomains corresponding to subsystems – a form of 'discretization'. (An ultimate partitioning or 'totally discretized design' might take the form of a connected collection of ideal elements – point masses, massless springs, and the like.) The issues exposed in this abstract view of design are quite subtle and not well served by my crude prose; those who want to learn more should consult Henry Paynter's lively discussion of the logic which led him to bond graphs [Paynter 61], and the brief essay by Shapiro and Voelcker [Shapiro 89]. The reason for raising these matters in any form is to emphasize that mechanical design is not naturally 'discrete'. The governing phenomena are

intrinsically spatially distributed and continuous, and mechanical products that honor them presumably should have a similar character. (The last sentence is weak; I believe a much stronger case can be made, but I cannot conjure it on short notice.)

\*       \*

A final comment on design: many successful companies which claim to be manufacturers of mechanical goods really do no or very little manufacturing. They design products, they market products, and sometimes they assemble products, but they 'out-source' almost all part-making. This simple fact says a lot about where 'value-adding leverage' lies, and it explains some important but largely hidden characteristics of our industrial infrastructure. To give but two examples of the latter: (1) standards, e.g. for mechanical drafting and tolerancing [ANSI 82], play a critical role in allowing out-sourcing to work, and (2) the primacy of design over manufacturing has biased the development of mechanical CAD/CAM systems in unexpected directions.

## MANUFACTURING PROCESSES

Some 200–300 distinct 'unit manufacturing processes' are in active industrial use today; Figure 2 provides a taxonomy for discussing them. Some are more than 5000 years old, and until very recently none were understood in scientific terms ... meaning we had no mathematical models for their operation or effects.

While a lot could be said here about processes, the pertinent facts for our current mission are probably these: (1) different processes have different effects on materials, and generally do more than merely change the shape of a workpiece, and (2) probably 1/4 to 1/2 of today's 200–300 processes are necessary to effect the material transformations required by contemporary designs; the notion of standardizing on a small number of processes (less than ten, say) to make everything is simply not viable. (The current set of 200-300 processes contains 'functional equivalents', in the sense that some processes can replace others if, for example, the production volume warrants the use of special tooling.)

## SOME DISTINCTIONS AND CLARIFICATIONS

### *On process independence*

An early version of the 'New Paradigms' white paper by Hilibrand and Chern claimed that VLSI design is independent of the VLSI process. The current version corrects this by citing (on p.2) a clean *separation* between the VLSI manufacturing process and design, and by noting that VLSI design systems embody process constraints. (The initial claim was clearly wrong; VLSI designs done under current design rules can *only* be fabricated by the process reflected in the design rules, and hence are highly process-dependent.)

Mechanical design has been governed for the past few decades by a doctrine of strict process independence (except for parts or products made wholly in-house or by captive suppliers): see Section 1.4(b) of [ANSI 82]. In earlier times designers were allowed to specify parts via notes on drawings, such as "Drill and tap 1/4" x 20 NC", or "Rough-mill Slot C then grind Face D", but now such process-dependent statements are prohibited. The current nostrum: specify precisely the result you want in geometrical and material-property terms, *not* how to obtain it.

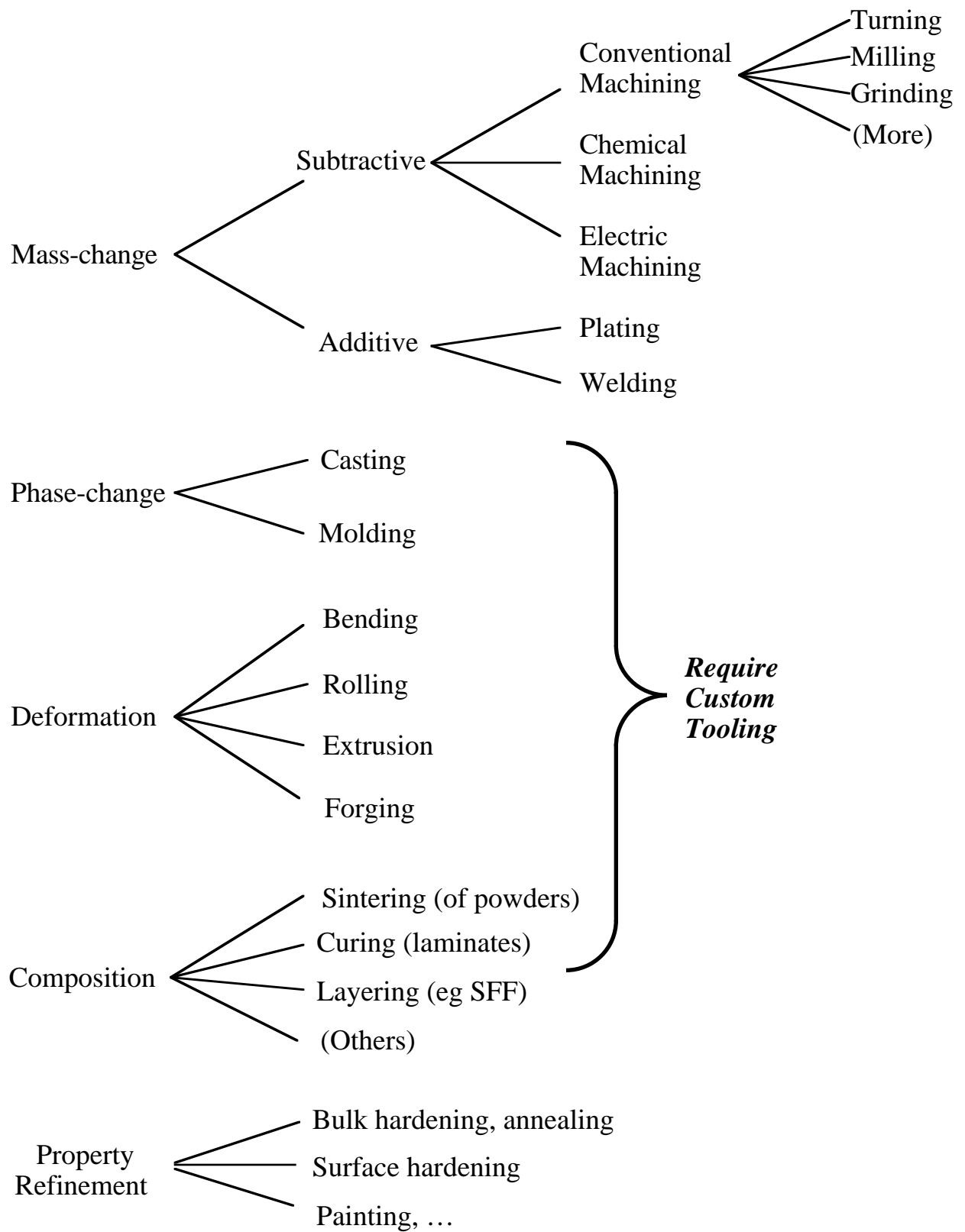


Figure 2: Manufacturing processes.

### *On 'virtual prototyping'*

'Virtual prototyping' is a mildly annoying (to me) buzz phrase that a few people may think is a 'new idea'. It seems to mean computational part or product modeling, coupled with performance simulation or performance analysis. Mechanical engineers have been trying to do this since the days of mechanical calculators (or earlier), and now the tools – computers *per se*, software for solid modeling, software for kinematic and dynamic analysis and simulation, etc. – are beginning to match the more modest of our aspirations.

### *On 'virtual manufacturing'*

Similar remarks apply. The underlying mechanisms are computational process models – specifically, process:workpiece interaction models, residual workpiece-effects models, and much more easily, workpiece transport models (for use in factory routing and similar logistics exercises). Again, mechanical engineers have been trying to do this for 20-plus years, and we are now achieving some successes in limited domains, e.g. machining, robotic manipulation, relatively simple mold-flow and deformation processes.

## **... AND FINALLY ...**

It is time to end this screed. Let me do so with two questions, from several or many that could be asked.

- 1) There are major gaps in our understanding of mechanical design, with perhaps the biggest being the lack of means for specifying mechanical function – what a product is supposed to do – in a constructive mathematical manner. The operative word is 'constructive' ... will the specification help us to move mathematically from function to configuration to form?

Does VLSI technology carry lessons for bridging this gap? What are the specific relations that link Boolean and sequential specifications of 'function' to multi-layer silicon? Do they suggest mappings to alternative implementations?

- 2) Might VLSI technology be stuck on a technological and perhaps conceptual plateau? The lines get narrower and closer and the logic densities and clock speeds increase, but that's just 'more of the same'. Are there lessons to be learned from mechanical domains? Is it time to consider distributed-parameter logic over a silicon continuum? What about genuine 3-D VLSI, with embedded heat pipes or micro-channel cooling?

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### 3.4.12. POSITION PAPER BY AMAR MUKHERJEE

#### SOME THOUGHTS ON NEW PARADIGM FOR MANUFACTURING

Amar Mukherjee  
University of Central Florida  
April 19, 1994

#### Information vs. Energy

A fundamental difference between VLSI medium and the mechanical or electromechanical medium is that the VLSI circuits essentially perform an *information processing* task whereas the mechanical devices *transform energy* or act as transducers of energy. The physical properties of the materials for VLSI circuits matter only in terms of their effects in *realizing* an abstract function of computation or communication. A variety of technologies could be used at the lower level to implement the abstract operations at higher level. The design process at higher level can be captured by formal systems like Boolean algebra, state graphs or programming languages such as VHDL. We can talk about systems at the behavioral level or architectures at functional or RTL level or even logic gate levels without worrying about the lower level technologies that implement them. Such a paradigm is not applicable to mechanical or electromechanical design. Since the primary task of mechanical devices is to transform energy, their design specifications involve actual physical parameters such as mass, force, temperature, time and dimensions in space. The implication of this is that for VLSI circuits there exists a clean separation between manufacturing process and the design efforts. It allows the designer to use higher level tools for design, simulation, validation and testing independent of target technology and independent of the specific system being designed. Mechanical systems specifications require knowledge of process-dependent lower level physical parameters and therefore the design process cannot yet be decoupled from the fabrication process. Finding suitable abstractions of mechanical and electromechanical parts or indirectly discovering a Mechanical Design Language (MDL) - a VHDL-like language for mechanical design will certainly be a challenging problem for future research.

#### Controlled vs. Natural Environment

The VLSI circuits are embedded in an artificial environment which can be controlled very accurately. For example, a data book description of a family of logic cells provides complete information about the environment where these component cells can work properly. Any arbitrary system can be designed as long as the boundary conditions or the input/output specifications of each component part are not violated. The system does not dictate the specific definition of a particular cell; the system specification is translated into an architecture which can best be mapped onto the cell library with its encapsulated environment. The initial choice of the library cells, however, may depend on some generic trends common over the family of systems. For mechanical or electromechanical systems, the properties of the components are dictated by the system which must work in a *natural* environment which cannot be controlled by the designer. Thus, the components that build an automobile or those that build an aircraft or a ship have drastically different properties and characteristics because the environments of operating an automobile, an aircraft or a ship are totally different. This underscores a basic difference between mechanical and VLSI manufacturing since a standard industry process for mechanical manufacturing cannot meet the design requirements of various systems.

#### Linear vs. Nonlinear Geometry

For VLSI designer, the end product of the design process is a two-dimensional description of layers of masks which guide a set of material layering steps interspersed with diffusion and ion implantation steps. The structures that are actually created on the wafer surfaces are simple rectangular blocks which can be described by a set of linear equations. In the VLSI world, there is no need to produce non-polyhedral quadric bodies (cone, sphere, cylinders etc.), superquadrics or complex non-linear object shapes for which no closed form mathematical descriptions exist. Extending the domain of

geometric coverage of solid modelers that use CSG (Constructive Solid Geometry) based models and converting these models efficiently to boundary representation (BREP) for machining and finite element analysis are active fields of research today. A solid modeler capable of describing and representing objects of real world at the front end of a laser materials processing system will, I believe, become a primary tool for fully automated mechanical manufacturing system. The basic physical processes of laser machining steps are a very simple heat treatment of materials induced by a beam of monochromatic light to perform cutting, welding, drilling or cladding operations, and unlike VLSI processing do not involve any sophisticated solid-state phenomena. The difficult part is to automatically guide the movement of the laser beam to produce real-world objects. Lasers coupled with computer-controlled processes, NC system and robotics currently exist but none has yet been developed which is independent of the specific process or system being produced. Needless to say, that development of Laser Guidance System language having the power and generality of a high level-programming language will be an important topic of future research.

## **Complexity and Scalability**

The complexity of a VLSI circuit is sometimes expressed in terms of the number of transistors in a chip. The complexity is related to design rule parameter " $\lambda$ " which characterizes the minimum feasible line width of a process. The VLSI manufacturing processes have steadily been *scaled* down during the last two decades, putting millions (some predict a billion by the end of the century) of transistors in a chip. As we build bigger chips, we can incorporate more functionality and create new and innovative architectures for digital systems.

Such a concept is not directly extendable to mechanical domain and scaling down a process to put more components does not necessarily produce new functionality and power of the system. What microminiaturization can do is to open up new possibilities such as resistor trimming in thick and thin film circuits, labeling of silicon wafers, repairing a VLSI circuit by vaporizing defective connections and putting right connections by laser scribing, laser drilling of magnetic recording heads for disks and tape drives. But more dramatic advances will come from the use of microtechnology to create mechanical systems that operate at micron levels. Micromachining has already been used to design silicon strain gauge for measuring heart muscle, silicon microflow sensor, accelerometer, neural probe, silicon turbine and silicon electrostatic motors. These devices have been produced by three-dimensional sculpting of silicon using standard semiconductor processing. In order to produce components using different kinds of materials and linkages, it will be necessary to use a combination of semiconductor processing and laser micromachining. This will be one of the most promising fields where the so-called VLSI experience will be quite relevant.

### **3.4.13. POSITION PAPER BY GENE MEIERAN**

#### **WHAT CAN MANUFACTURING IN GENERAL LEARN FROM VLSI MANUFACTURING IN PARTICULAR?**

**Gene Meieran  
Intel Corp.  
April, 1994**

The art of manufacturing in general has been going on for a lot longer than VLSI manufacturing. However, VLSI manufacturers have made significant strides in manufacturing, which has allowed them to market products of essentially four orders of magnitude more complexity over a time period of two decades, for essentially a constant price. The question is, what did VLSI manufacturers do differently, and if they indeed did something different, what can we learn from this experience to help the more traditional mechanical product manufacturers?

VLSI manufacturing can be viewed as a three step process: the design of a product that can be manufactured as a sequence of detailed processing steps, the creation of a monolithic wafer that contains numerous identical chips, processed INTO a silicon wafer by means of sophisticated lithography and minute processing steps, and the assembly of separated chips into packages, along with testing of these packaged devices.

This final assembly and test step is along the lines of conventional manufacturing, and it appears that there are few lessons to be gained here that will improve the general state-of-the-art of mechanical manufacturing, other than the ability to manipulate and assemble very small devices into very complex board assemblies. But this is more or less standard technology.

However, both the design and wafer fab processing steps do include novel technology; whether or not this new technology can be emulated to help in the manufacture of more traditional mechanical products, remains to be seen. But let's look at the possibilities.

#### **A. Design**

In one sense, design of VLSI products is quite simple; there are a limited number of active and passive elements that can be integrated into an extraordinary number of physically similar but functionally different electronic devices. Memory chips, micro controllers, logic and analog devices all look alike, and are fabricated in silicon wafers, using a variety of lithography, thin film deposition, diffusion and ion implantation and etch processes. The differences between process sets is in the sequence and detail of these individual process steps, and the differences between products within one process set, are simply due to the differences in the masks used in the lithography process step. From combination of these basic elements, literally millions of different products can be manufactured.

The design process itself is simple in one respect, due to the small number of elemental pieces that make up an electronic device; transistors, resistors, capacitors, interconnects, passivation films, etc. However, in another respect, the devices are exceedingly complex, in that millions of these individual elements must be connected 100% correctly, each with a very rigidly controlled set of characteristics, if these complex devices are to function.

So the design paradigm is to connect millions of but a few types of individual components, into an organizational pattern that represents the chip architecture, with 100% accuracy with regard to element size, placement, and characteristics. This is typically a process that is best carried out by use of sophisticated computational tools, supported by exceedingly good models of both the product characteristics and process step characteristics.

The three secrets to design, then, are:

1. A product design and architecture that is robust, highly functional, and very complex. The chief ingredients are people who are very computer tool literate, and who have an in-depth understanding of the functionality of semiconductor chips.
2. A set of design tools that makes the integration of a huge number of individual components into a fairly routine activity. The tools are very powerful, and due to the complexity of the operation, contain many automatic routines to make sure the steps are carried out correctly. These include automatic placement of chip elements (pieces of the design that have distinct functions, which are integrated into the full chip, such as memory, I/O, logic, etc.). Since zero errors can be tolerated even in design of a circuit containing millions of individual elements, these tools must replace the human activity of inspection for defects and errors.
3. A set of comprehensive models that allows the chip designer to experiment in the space of process trade-offs; what if the chip looks like this vs. like that; what is the resultant functionality? The fact that complete models of the product and process exist makes it possible to design chips of incredible complexity that work the first time. Since it takes on the order of weeks to actually manufacture a chip, the rapid growth of the semiconductor industry would not be possible if one had to wait weeks or months to try to find out if some element combination or permutation, actually improves chip performance.

## **B. Processing**

The manufacture of semiconductor devices is in some sense no different from the manufacture of other kinds of sophisticated products: pharmaceuticals and petroleum products, to name a few. In all cases, a material is created whose characteristics are determined by very precise control of chemistry. The major distinction between these industries and the semiconductor industry is scale; semiconductor products contain VERY SMALL components, so that much of the work is done at high magnification under strict computer control, since human beings are unable to perform these tasks.

This is fundamentally different, for example, from making cars, where humans COULD make a car and automation is used to speed up the manufacturing process. In the semiconductor industry, in addition to increased productivity through automation, automation plays a central role in control of the process in order to enable the process to work, much less reduce costs.

In principle, the thin film process used in VLSI manufacture is no different from painting a car; a coating is put on the product in order to meet some specification. Indeed, one could draw analogies between ALL semiconductor processes and other product processes, except for the concept of scale. However, it must be noted that in the VLSI case, a point defect that in a paint job may be regarded as a visual defect, could kill the device functionality. Hence the emphasis on removing all sources of defects.

Scaling has caused our industry to invent new technologies, capable of meeting accuracies on the order of 0.1 micron on the part, and compositional sensitivities of 0.0000001 %.. As a result of these needs, a metrology industry has arisen that pushes the sensitivity and accuracy of conventional technology almost to the limit, and has caused the introduction of process control and adaptive process control, to an extent hitherto only dreamed about.

Scaling up in volume has been accomplished by use of the patterning of wafers with repetitive copies of an individual device structure, so that one wafer is essentially processed in parallel (except for the lithography step, which is sequentially repeated over the wafer surface). Hence, one can make copies of the same device at the same time. And since device sizes continue to grow even as the number of active elements on a device exponentially increase, wafer sizes grow to accommodate these larger devices. The fact that the process information is essentially carried in the layers of masks used to define device structures makes it easy to change products being manufactured at one time; simply change the mask sets.

The value to other manufacturing enterprises then arises from these three manufacturing paradigms: new, very precise metrology, processes and process control procedures, mostly computer controlled,



that can handle very small quantities of very small objects, and scaling of quantity through a significant amount of parallel material processing, combined with continual increases in the size of the wafers. Having a line of products whose only differentiation during manufacturing is to change the mask set, makes this into a very flexible, high volume manufacturing enterprise.

It is entirely possible that using such expertise can help other manufacturing facilities and enterprises.

### **3.4.14. POSITION PAPER BY PAUL LOSLEBEN**

#### **VLSI DESIGN METHODOLOGY AS THE RESULT OF SYSTEM-LEVEL DESIGN**

**Paul Losleben  
Stanford University  
April 21, 1994**

I'd like to take a slightly different cut at the topic of this workshop. If, in the late 1970's we had asked how we could make the VLSI design practices of that period easier, we probably would have only extended the direction slightly that design approaches of that period were already taking. Specifically, most VLSI designs were based on highly specialized circuit and process designs. This was the primary reason that design costs were "going to the moon" as Bill Lattin and later Gordon Moore were fond of saying. As you may recall, approaches to ASIC design, developed 15 years earlier, had not yet been very widely accepted by the electronics industry. There were a lot of reasons cited for this: too slow, too wasteful of chip area, no way to assure quality, poor learning curve opportunity, etc.

This changed when we began addressing the larger issue of system design instead of circuit/chip design. We discovered many efficiencies at the system level that we could trade for false efficiencies at the circuit, device and process design levels. Fortunately, we were building on a technology which was well suited for this. All the arguments that Dan Whitney and Carlo Sequin made in their position statements are valid to first order (although one might quibble with some of the details).

So, the question is, I think, not whether one can apply the VLSI experience to mechanical design (or other fields), but whether there is opportunity to apply basic technology (like semiconductor technology) in ways that yield the orders-of-magnitude improvements in product cost, performance or functionality. The enabler in the VLSI experience was the application of computing technology and I would claim that computing (and probably communication) technology is a strong candidate as an enabler in whatever we might find.

Semiconductors is the field that I understand best, so I'll begin with this as a candidate for new opportunities. The extraordinary advances that we have seen in the basic underlying technology have been fueled by the components (and ultimately systems) that this technology has made possible. The dual benefits of improved performance and improved functionality that we receive from reduced geometries (and no end in sight) have justified the large systematic investment in new technology. What a shame that we only use this technology for such a narrow range of products! The vast majority of components produced today are digital and based on simple MOS device structures. Yes, there is also some use of Bipolar devices and even an emerging application of micro-electro-mechanical (MEM) devices, but it seems clear to me that we have only just begun to understand what might be possible with this technology.

The problem, of course, is the extremely high cost of developing new devices (electrical or otherwise), the processes that might produce them and the equipment sets (factories) that will run the processes. The cost and time of this aspect of design is prohibitive. Of course, this is a very familiar scenario. Back in the early 80's when we first began thinking about mechanical analogies to VLSI, Danny Cohen made the now clearly obvious statement that the main reason VLSI and mechanical design were different was that mechanical design nearly always involved the design of the manufacturing process \*in addition to\* the design of the form/function of the product. So, if this is a barrier, how can we remove it? I am now going to take the contrarian position of changing the topic of this workshop from how we might make mechanical (or other) design more like VLSI to how we might learn from mechanical (or other) design to increase the potential for new applications of basic semiconductor technology. If you will then permit me an enormous leap of faith, perhaps we can then extend this to other basic technologies and other kinds of products.

Why is semiconductor device/process design so difficult? If it were easy to develop new devices and the processes needed to produce them, say by using synthesis and/or simulation in a "virtual

factory," then we could use the same representation to drive automated, flexible machines in a "programmable factory." This is, in fact, the focus of the work of several universities over the past decade. Device design is merely the downward extension of our familiar electronic design hierarchy, residing roughly between circuit design above and materials design below. Similar concepts span this hierarchy including the notions of separate views such as behavioral, structural and physical design. In VLSI, we merely choose to draw a line at some level in this hierarchy so that "system designers" do not need to dabble in the detail below. In ASIC, for example, we draw the line just above the circuit level so that the digital designer can concentrate most of his labor to the mathematically "nice" level of Boolean logic. This choice is based on the difficulty of designing at lower levels. At the circuit level and below, the mathematics becomes much more difficult and the understanding of the technology is incomplete. In reality, these levels of design cannot always be ignored. We are increasingly forced to consider effects at the circuit and device level as we push the limits of cost/performance. The important point is, I believe, not to eliminate design at this level, but to develop the computer tools needed to reduce design time/cost at these levels. The extent to which we are successful will be the extent to which new kinds of products become possible.

But, a new device structure also needs a new process to manufacture it! This is a greatly uncharted territory of design and contains many of the complexities that Dan Whitney cited for mechanical design. For example, the design of a single process step cannot be done in isolation. Like a gear in a transmission, any individual process step must "bear the load" of the steps before and after in transmitting its contribution to the final device structure. This is difficult, but not impossible. In fact, we can borrow a great deal from what we learned in CAD over the last three decades. Just as electronic circuitry is used to transform input and internal state to a new output state, by analogy so also does a semiconductor process transform input wafer state to output wafer state. Just as we design for electrical state transformation in electronics, so also can we design for wafer state transformation in semiconductor processes. Only the equations are more difficult! (How's that for an understatement!) As we learned in ASIC, optimization at the system level can provide beneficial tradeoffs over optimization at the lower levels of design. We are just at the beginning of understanding how we can trade off detailed optimization at the unit process level for benefits at the overall process flow. We are beginning to understand how to build libraries of process steps (our equivalent of the ASIC cell) and how we can use abstraction by composition to build process modules out of basic steps or even other modules. Sound familiar?

We know, at this point, that there is a great deal that we can borrow from the electronics design experience (of which the VLSI design experience is a part) to greatly reduce the time and cost of semiconductor device/process design. In industrial practice, we are achieving 50% reductions with \*very\* crude tools. Based on the concepts that we already understand, we know that we can achieve order of magnitude reductions. Within the next decade or two, we may see several orders of magnitude.

Why is this relevant? For two reasons. First, while we have not argued for a direct application of the lessons learned from the VLSI experience, we clearly see indirect application in the use of many very similar computing tools to the design of manufacturing processes. This work, ongoing at several universities will result in increased opportunity to build new and innovative products out of semiconductor technology. We cannot claim the same market pull for this as we saw for VLSI, but the long term potential is exciting. The second reason is more speculative (and probably more relevant to the intent of this workshop). If we admit the thesis that reducing the time/cost to develop manufacturing processes will help make it possible to invent and economically produce useful new products, then these methodologies may apply to other industries. The reader who is still paying attention will note that I have turned the question from how one might emulate the VLSI experience where there is a nice, well defined separation between design and the manufacturing process to how we can change semiconductor manufacturing and perhaps emulate \*that\* experience. If you agree to this diversion, then perhaps we can speculate about how universally useful this might be. Knowing no more about other industries than I do, I'm reluctant to make sweeping claims, but it certainly seems that advances in process design coupled with computer controlled flexible manufacturing has a lot of potential. This is already done in some continuous flow manufacturing in the chemical industry. It may be possible in others.

One final word. I have not addressed the issues raised by both Dan Whitney and Carlo Sequin about the differences on the product design side of the equation. Anticipating the positions that some of the others are likely to take, I'll leave that topic to them and keep my comments restricted to the process side.

### **3.4.15. POSITION PAPER BY JACK HILIBRAND**

#### **ANALOG AND DIGITAL IN VLSI SYSTEMS AND IN MECHANICAL SYSTEMS**

**Jack Hilibrand**

**Consultant, National Science Foundation**

**April 20, 1994**

The world of electronic systems was mostly analog before the VLSI era. The systems (radio, television, telephone, radar, sonar, etc.) were based on analog sensors, analog signal processing, analog power supplies, analog actuators, etc. Today these systems are almost all digital. During the past two decades digital electronics has not only replaced most analog electronic systems, but also some mechanical systems.

Time keeping is one of the most notable examples. At first digital watches replaced mechanical watches because digital watches didn't need to be rewound daily. However, there were soon other reasons. The basic timing element, a quartz crystal oscillator, was more precise than the mechanical spring and regulator. Digital watches were more rugged than the mechanical watches. Initially digital displays were used, but soon it became clear that people preferred to use the analog displays they were accustomed to and most digital watches were built with analog displays. The intervals between battery replacements were steadily lengthened by shifting from bipolar electronics to CMOS and by going from LED displays to liquid crystal displays. Additional functions were added, because it was easy to do so with digital systems, functions such as day, date, timers, alarms, reminders, data files, etc. Today mechanical watches are used, mostly, by older people who retain a nostalgic feeling for them. Electronic watches of good performance have become so inexpensive that they are a fashion item, changed each day to match the dress a woman wears. The point is that although mechanical watches are still being made in the old way, the market for such watches has been preempted by the lower price and improved performance of digital watches.

We need to look at other mechanical systems to see how some of them are changing and how others can be changed to take advantage of digital electronics. Let's examine some of these transitions that are underway and some that are still in the future.

Automotive systems are at the conceptual center of the world of mechanical systems. However, automotive systems have adopted electronic subsystems on a grand scale. Initially, to meet emissions requirements, the ignition systems in many cars were changed from a mechanical linkage (with an electromechanical switch (the "points") that opened to cause the spark in each cylinder into an electronic controller (with a power transistor that created the spark pulse). Many mechanical automotive subsystems were changed to electrical, like windows and door locks, seat belt reminders, electrical clocks, etc. The proliferation of micro-controllers is continuing and the control systems are being linked into a single wire (a data bus) carrying multiplexed signals coded to effect the specific actuator needed. In the process, mechanical linkages are being eliminated. The tachometer/odometer/speedometer system is evolving into an electronic sensor and an electronic (often digital) display separated in space and connected by wire. The speedometer cable, which directly transmitted mechanical rotation from the transmission to the dash, is replaced by a single wire. There is still a long way to go, with the timing functions inside the engine still relying on camshafts and timing belts, but, clearly, the time is coming when electronic sensors and electronic actuators connected by a digital system will control the engine. What was a mechanical system, manufactured using mechanical techniques is evolving into a microelectronic system manufactured using VLSI techniques embedded in a mechanical framework. There is little need to learn to build crankshafts in VLSI fashion (if that were possible) when the crankshaft and the cams it drives can well be replaced by an electronic timing system by the end of the decade. The drive shaft is harder to replace but tests of turbine generators with electrical motor drives have started and may someday replace the main power drive in automobiles (if battery-driven electric cars don't get there first).

Airplane design is similarly evolving toward a fly-by-wire approach as the hydraulic lines for controlling the steering and elevation surfaces are replaced by wires transmitting control signals to

actuators at the surfaces involved. The instrumentation retains an analog look, but many of the instruments read the analog output of a digital system that takes sensor inputs, converts them to digital form, processes them in digital form, transmits in digital form to the instrument and converts the output to an analog readout. High performance fly-by-wire aircraft can most economically be achieved with electronic controls but use hydraulic lines for backup. The airframe itself is built using mechanical manufacturing techniques but the innards are increasingly microelectronic in nature and at least some of the mechanical design requirements are becoming less stringent since the control system overall is being simplified.

In one of the most recent changes, the video camera business is adopting electronic image stabilization that is based on processing the video signals to minimize the effects of hand-motion and vibration. Only recently movie technology perfected mechanical stabilizers intended to let the cameraman move while filming the action. Such stabilizers depended on using rotating flywheels in three axes to provide stability at the cost of significant added camera weight. Now the image on a CCD sensor can be stabilized in equivalent fashion without any perceptible increase in weight. The ability of microelectronics to handle the signal in digital form and to provide features and capabilities in that form leads to the more general question: Can the difficult part of mechanical systems design be replaced by system simplification of the mechanical system and by performing the difficult task in the microelectronic domain? Can we replace the mechanical drivers by stepping motors and solenoids? Can we replace the position sensors by laser interferometric tables?

If we find that it is difficult to build mechanical systems using VLSI approaches, will it be possible to replace the part of the mechanical system that needed precision and that stressed the materials to their limit by combining microelectronic elements and macro electrical actuators with a less sophisticated mechanical structure more amenable to simplified manufacturing techniques and multiple applications where there is more design margin? More directly, if we can simplify the mechanical design by putting the complexity in the electronics, will we be able to go to standardized mechanical structures where the process and the configuration are decoupled?

The path that analog electronic systems followed was: replacement of analog components and computers (that were at the limits of process capability) by a/d conversion and digital processors. The advantages of digital include reduced noise and reference signal drift, ease of processing with elements that, once provided, can perform other ancillary functions of significant value, capability of separating process from design, simulation and emulation capability and, finally, the benefit of making the transition from a very specific analog control system design for a single unique application to a generalized abstract control system model that is useful in many other applications and with capability to spare for new functions and higher performance. To gain such advantages and to be able to implement the VLSI paradigm for manufacturing, it would seem desirable that mechanical systems be “digitalized” to whatever extent possible. We must seek to develop the conceptual framework within which this transformation can be promoted.

The present status of this “digitalization” process is that one product area at a time is being implemented, with little reference to other product areas. The challenge is to create a generalized system design methodology that examines a mechanical system design requirement, separates the high power, high mechanical stress activities from the low power control activities, analyzes the control requirements to provide a microelectronic implementation and deals with the overall design in terms of a mixed mechanical/electrical system. One guideline might be that the low power level information processing activities should be implemented in digital microelectronic fashion while the overall structure and high power level activities need to be done using mechanical design principles. Standardized components need to be defined for conversion of analog sensor inputs to digital form and for providing the desired mechanical output. Embedded processors could be used for the control system providing capability for expanded function. The simplified mechanical structure, with reduced design requirements, could now be built in a more standardized fashion (without the specialized attention that is needed when there is little design margin in a challenging system implementation).

This workshop can examine the mechanical system design process to further ask what can be done to provide infrastructure, educational support and tools for the process. What research activities could

make this design path more generally usable? Are there instances where a strictly mechanical system approach is more cost effective and can we identify such systems?

### **3.4.16. POSITION PAPER BY DANIEL D. GAJSKI**

#### **WHY THE VLSI DESIGN METHODOLOGY WORKED**

**Daniel D. Gajski**

**Univ of California, Irvine**

**April 29, 1994**

The success of VLSI technology can be attributed to the simplicity of CMOS technology and the existence of cell libraries, CAD tools and a simple methodology for creating complex products. I believe that layered manufacturing and a clean separation between the manufacturing process and product design were of secondary importance.

The main contribution of the Mead-Conway methodology was that it simplified the layout design process by introducing less than a page of layout rules. Before its introduction, VLSI layout was a "black art" practiced by few designers in each company. Furthermore, each company had different fabrication processes that were specified by 30 to 50 pages of layout rules. Mead and Conway reduced those 30 to 50 pages to only a few rules that could be learned in less than one hour.

The second reason for VLSI success is that there are very few objects in the CMOS technology. Every product consists of P and N transistors, contacts and wires. In general, each product differentiates itself in only parameters, the transistor configuration and transistor sizes. Therefore, it was easy to teach, learn and design circuits with different functionalities.

The VLSI technology was able to exploit the advantage of hierarchy and replication--two simple concepts for controlling complexity--through the introduction of libraries and a well defined set of abstractions in the design process. The standardization of abstraction levels was necessary for the formalization of the design synthesis. Thus, libraries and abstraction led to CAD tools that simplified the design process even further.

There is no reason to believe that similar advantages can be achieved in manufacturing of other products. One of the difficulties in electromechanical manufacturing is that mechanical designs are three-dimensional, while VLSI designs are two-dimensional. However, with the increasing power of workstations and the availability of computing, three-dimensional CAD tools should be made available as two-dimensional CAD tools were available for VLSI in the 1980's.

Similarly, the establishment of description languages for mechanical parts, similar to CIF in the 1980's, is needed to clearly separate manufacture and design processes. Development of libraries and abstraction levels should be encouraged to simplify the design process.

Since electromechanical manufacturing is more complex than VLSI was in the 1980's, I would suggest attempting VLSI paradigm in selected product classes and selected industry. Furthermore, this paradigm should be introduced in phases and its success evaluated after each phase.

One proposed area would be multimedia packaging for electronic products where a limited number of mechanical parts is needed, namely those to communicate with the user, such as keyboards and displays. Those products also require a very limited number of moving parts, which makes them a good candidate for the first electromechanical MOSIS.



## **3.5 PANEL PRESENTATION - VLSI-ORIENTED RAPID PROTOTYPING TECHNOLOGIES FOR MECHANICAL PRODUCTS**

### **3.5.1. PANEL PRESENTATION BY R. MERZ ET AL.**

#### **SHAPE DEPOSITION MANUFACTURING**

**R. Merz, K. Ramaswami, F. B. Prinz, M. Terk, and L. E. Weiss,  
Carnegie Mellon University  
The Robotics Institute and  
The Engineering Design Research Center**

#### **Abstract**

One challenge for solid freeform fabrication has been to develop the capability to directly create functional metal shapes which are dense, metallurgically bonded, geometrically accurate and with good surface appearance. Shape Deposition is a manufacturing paradigm which attempts to address these issues. It incorporates the advantages of several processes including solid freeform fabrication (complex geometries, rapidly planned), 5-axis CNC machining (accuracy, smooth surfaces), shot-peening (for stress relief) and “microcasting” (a high-performance, weldbased material deposition process). These processes are integrated within a CAD/CAM system using robotic automation. This paper will present the current research in this effort.

#### **Introduction**

While functional metal shapes have been built with solid freeform fabrication (SFF) through postprocessing and/or conversion methods [1], it remains a goal to be able to *directly* build high performance metal shapes. Metal parts which are fully dense, metallurgically bonded, have accurate dimensions and good surface appearance are often required for such applications as fabricating custom tooling (e.g. injection molds) and functional production-ready prototypes (e.g. engine components). An early system, called MD\* [2], built prototype metal shapes directly with thermal spraying. While the MD\* approach incorporates a versatile material deposition process, it has several limitations which are also common to several other SFF processes. The parts exhibit a stair-step surface texture and it is difficult to achieve the accuracy, precision and resolution which can be achieved with traditional shaping methods such as CNC machining. Sprayed material also exhibits porosity, and the mechanical strength is poor compared to cast or welded materials. In addition, the buildup of residual stress through thermal gradients during layered solidification can lead to warpage and delamination [3].

Other incremental material deposition approaches which are based on welding, such as Shape Melting [4] and 3D-Welding [5], produce superior material properties, but have been limited in geometric complexity and require finishing machining operations. In our experience, no single SFF or conventional fabrication process will satisfy all the requirements for rapidly and *directly* creating high performance metal parts. To address this challenge we are investigating an approach called Shape Deposition Manufacturing (SDM) [10 - 14] which combines the benefits of SFF (quickly planned, independent of geometry), CNC milling (i.e., accuracy and precision with good surface quality), weld-based deposition (i.e., superior material properties) and shot peening (i.e., control of internal stress buildup). This paper describes the concept of Shape Deposition, a novel, weld-based deposition process called microcasting and thermal and stress related issues. Further, a testbed implementation of SDM is discussed and examples are presented.

#### **Shape Deposition**

The basic steps for building parts with Shape Deposition is depicted in Figure 3.5.1.1. To form each layer the growing shape is transferred to several processing stations. First, the material for

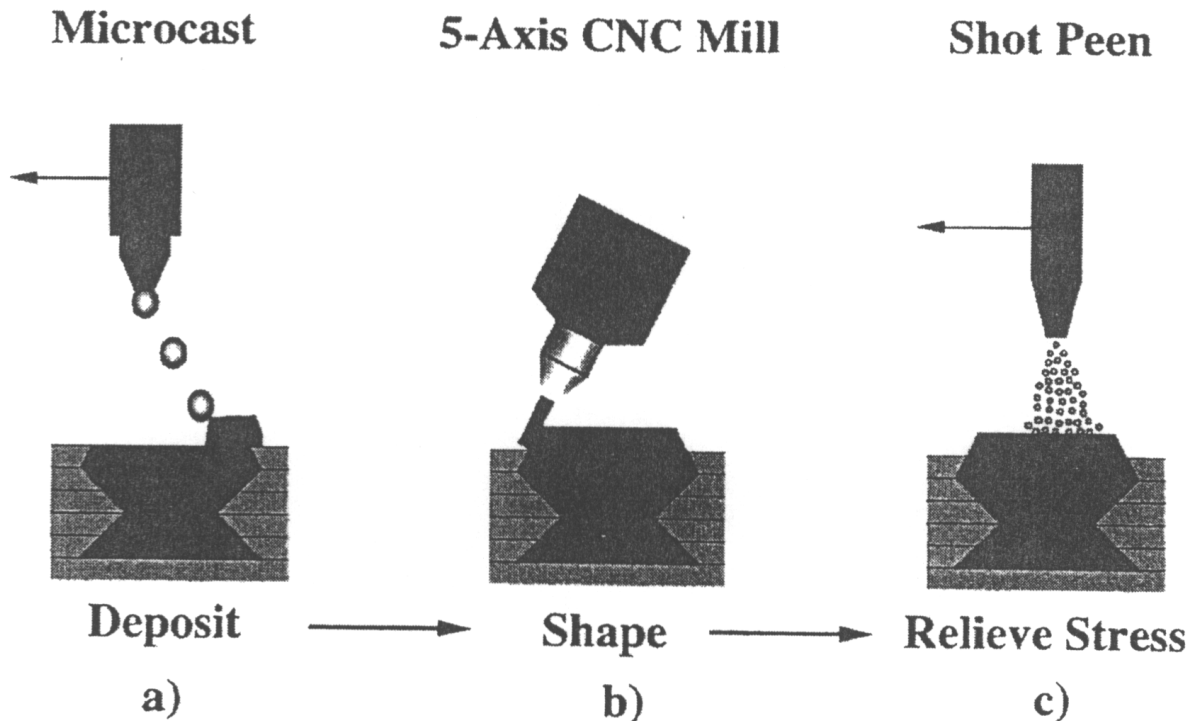


Figure 3.5.1.1 - Creation of a layer using SDM

each layer is deposited as a near-net shape using a novel weld-based deposition process called microcasting [7] (Figure 3.5.1.1a). The part is then transferred to a shaping station, such as a 5-axes CNC milling machine, where material is removed to form the net shape (Figure 3.5.1.1b). In the next step the part is transferred to a stress-relief station, such as shot-peening, to control the buildup of residual stresses (Figure 3.5.1.1c). The part is then transferred back to the deposition station, where complementary shaped, sacrificial support material is also deposited. Each of these operations are described in detail below.

In contrast to SFF processes, Shape Deposition decomposes the CAD model of the part into slices which maintain the full three-dimensional geometry of the outer surface. The total layer thickness and the sequence for depositing the primary and support materials depends upon the local surface geometry. Consider the shape in Figure 3.5.1.2 which represents three fundamental features which can be found in a layer; non-undercut (relative to the build direction), undercut, and a combination of both.

This shape can be formed as follows:

In the first layer, which contains only non-undercut features (Figure 3.5.1.3), the primary material is deposited (Figure 3.5.1.3a) and shaped (Figure 3.5.1.3b) first. This layer is completed by depositing the support material (Figure 3.5.1.3c) and planing the top surface (Figure 3.5.1.3d).

The second layer, which contains only undercut features (Figure 3.5.1.4), is created by depositing (Figure 3.5.1.4a) and shaping (Figure 3.5.1.4b) the support material first. This forms a molding cavity into which the primary material is then deposited (Figure 3.5.1.4c) and the layer is finished by planing the top surface (Figure 3.5.1.4d).

For the third layer the support material must be subdivided (Figure 3.5.1.5). The section of the support material with no undercuts is deposited and shaped first (Figure 3.5.1.5a). Next, the primary material is deposited and the non-undercut surfaces are shaped (Figure 3.5.1.5b). Finally the

remaining portion of the support material is deposited and the layer is planed (Figure 3.5.1.5c). In general, for layers containing a combination of undercut and non-undercut surfaces, the individual

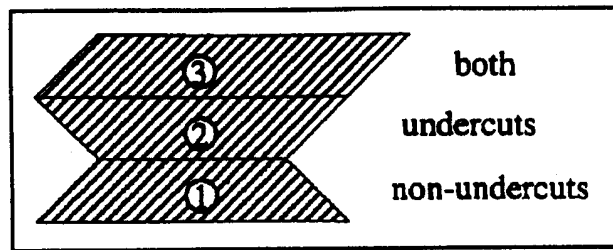


Figure 3.5.1.2 - Cross-section of example shape

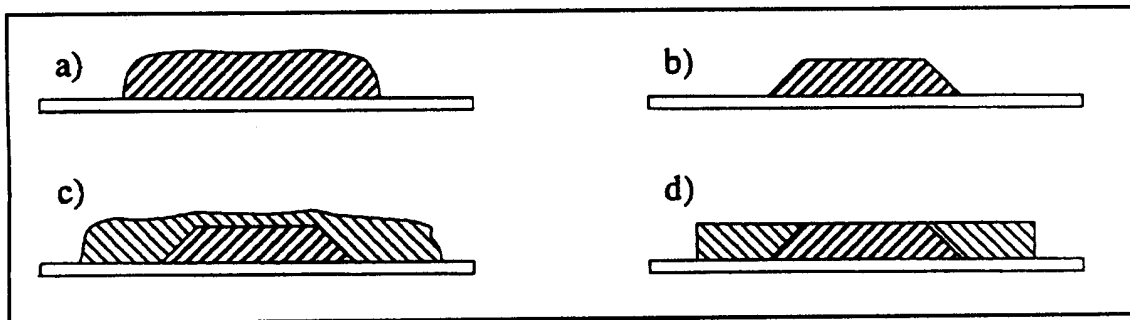


Figure 3.5.1.3 - Manufacture of non-undercut features

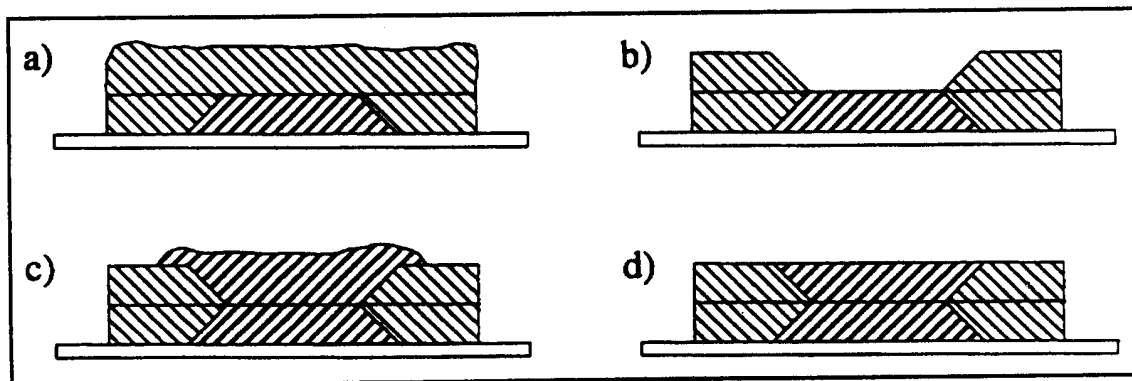


Figure 3.5.1.4 - Manufacture of undercut features

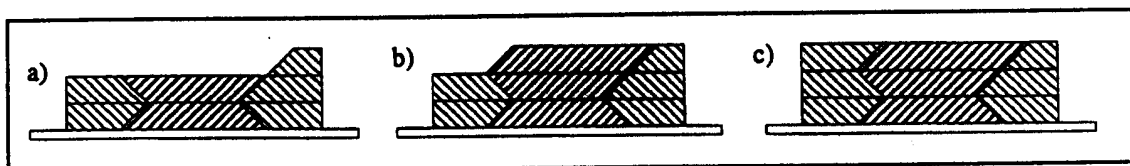
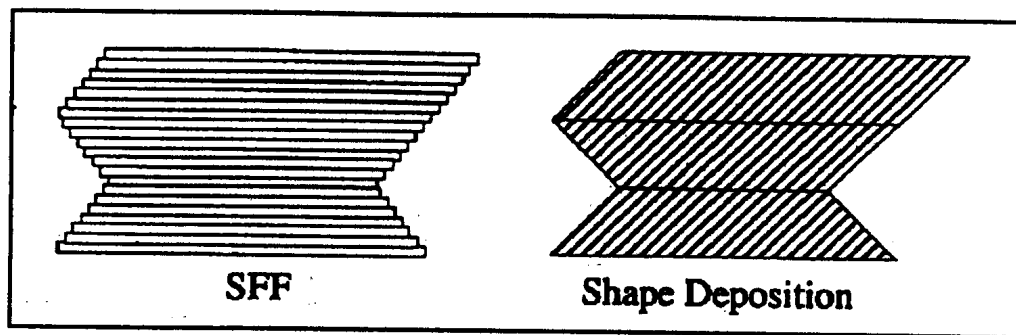


Figure 3.5.1.5 - Manufacture of arbitrary layers

materials have to be split into smaller segments. Each segment contains undercut surfaces only in those areas which are adjacent to previously deposited segments of the layer.

Figure 3.5.1.6 shows a comparison of cross-sections of the part manufactured with SFF techniques and Shape Deposition. While SFF needs a relatively large number of layers Shape Deposition can produce thicker layers and eliminates the stairstep texture of the surface.



**Figure 3.5.1.6 - Comparison between SFF and Shape Deposition**

## **Microcasting**

Thermal deposition technologies have been investigated in SDM in order to produce high quality material. However, conventional deposition approaches including thermal spraying and welding have several limitations. The molten droplets created by thermal spraying are relatively small (order of magnitude 50 micron) and therefore do not contain enough heat to remelt the underlying surface. Instead, mechanical bonds are predominately formed, and adhesive and cohesive strength are relatively low. While this leads to undesirable material properties, the low heat transfer into the substrate preserves previously shaped layers. In contrast, weld-based deposition approaches, such as MIG or plasma welding, locally remelt the substrate where the feedstock material is deposited, thus forming metallurgical bonds. However, the relatively large heat transfer will affect the shape of underlying material.

A compromise between thermal spraying and welding is required to achieve metallurgical bonding without destroying underlying geometries. Microcasting is a droplet-based deposition process which addresses this challenge. In contrast to the droplets produced with thermal spraying, microcast droplets are relatively large (1 to 3 mm dia.). They contain sufficient heat to remain significantly superheated until impacting the substrate, and rapidly solidify due too significantly lower substrate temperatures. The microcasting apparatus can be implemented with conventional welding equipment configured in a non-transferred mode [11]. Microcasting creates a stream of individual droplets at a rate between 1 and 5 droplets/second. By controlling the superheat of the droplets and the substrate temperature, conditions can be attained, such that the impacting droplets superficially remelt the underlying material (on the order of 10 micron deep) [6] leading to metallurgical interlayer bonding.

Microcasting is used to deposit not only the primary material but also the material for the support structure. One suitable combination of materials is stainless steel for the main material and copper for the support structure. The copper support structure is etched away with nitric acid after the part has been completed. When the stainless steel is deposited it does not deeply penetrate the copper because of the high thermal conductivity of copper. On the other hand, the copper does not deeply penetrate the stainless steel because of its lower melting temperature [7].

In thermal deposition internal residual stresses build up due to thermal gradients between the freshly deposited molten material and the previously solidified layer. Internal stresses can lead to warpage and to delamination. In order to control the build up of stress we are investigating to shot-peen each layer [8]. Small round metal spheres (called 'shot') are projected at a high force against the surface

in a blasting cabinet. Peening imparts a compressive load which counters the tensile load of the internal stress field.

## Testbed Facility

In order to have the flexibility to investigate different subprocesses, robotic automation was used to implement the SDM process [9]. The testbed facility (Figure 3.5.1.7) consists of four processing

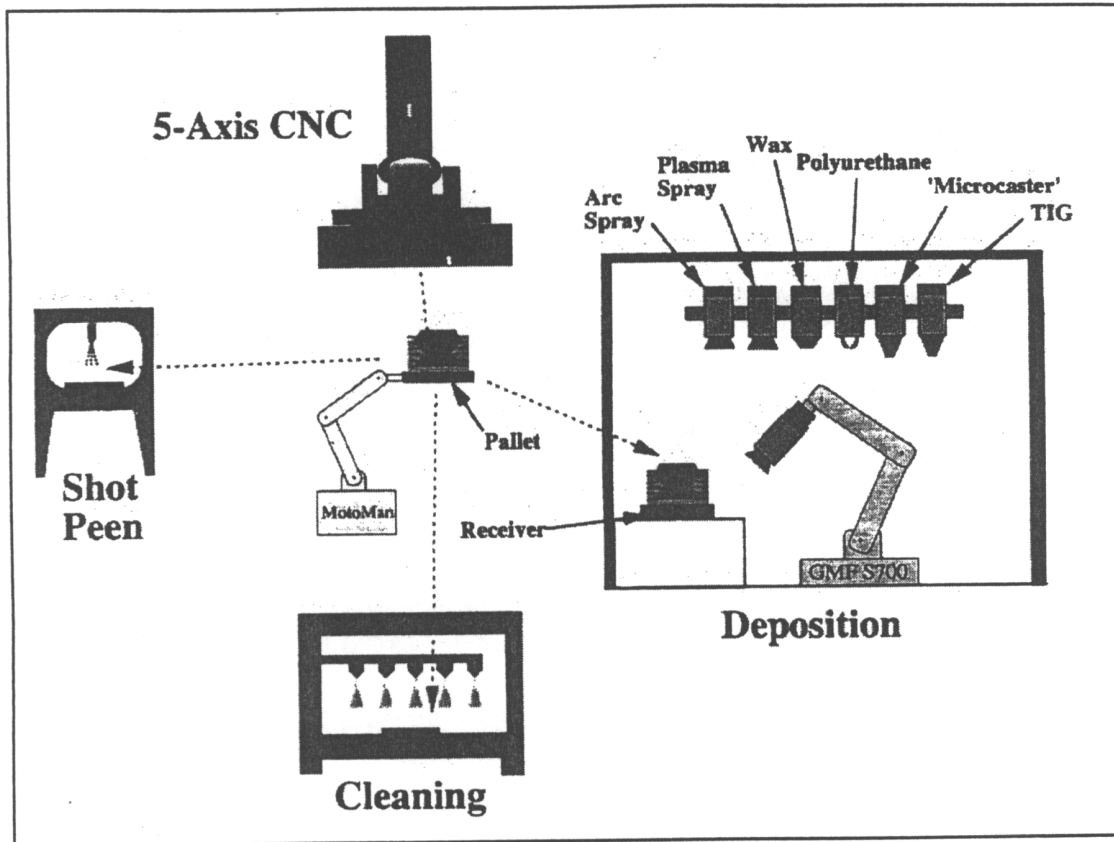


Figure 3.5.1.7 - Shape Deposition lab configuration

stations; CNC milling, thermal deposition, shot-peening and cleaning. The growing parts are built on pallets which are transferred from station-to-station using a robotic pelletizing system. Each station has a pallet receiver mechanism. The part transfer robot places the pallet on the receiver which locates and clamps the pallet in place.

The deposition station consists of an acoustic chamber (for noise abatement and dust containment), an air handling system (for dust filtration and collection) and a robotic deposition system. The deposition robot is equipped with a tool changing wrist and is able to acquire one of several different deposition torches which are mounted to a docking mechanism. The current sources include arc and plasma sprayers, as well as MIG, plasma and 'microcasting' welders. To deposit material, the robot picks up the appropriate torch and manipulates it over the growing shape.

The shaping station is a 5-axis CNC milling machine with an 21-head tool changer mechanism (i.e., it can automatically acquire one of 21 different end-mills). The hydraulically-actuated receiver used in this station is able to repeatedly locate the pallet within approximately 0.0002 inches. When cutting fluids are used in milling operations, the pallet is then transferred to a cleaning station to remove residuals. The shot peening station, which uses a conventional pressurized media delivery system, also incorporates grit-blasting capabilities for surface preparation prior to conventional spraying operations.

## Examples

While the Shape Deposition process is at an early stage of development, we have built several test parts. For example, Figure 3.5.1.8 shows a complexly shaped artifact which was made for the IMS (Intelligent Manufacturing Systems) consortium. This is a 308 stainless steel part which was embedded in sacrificial copper support material.

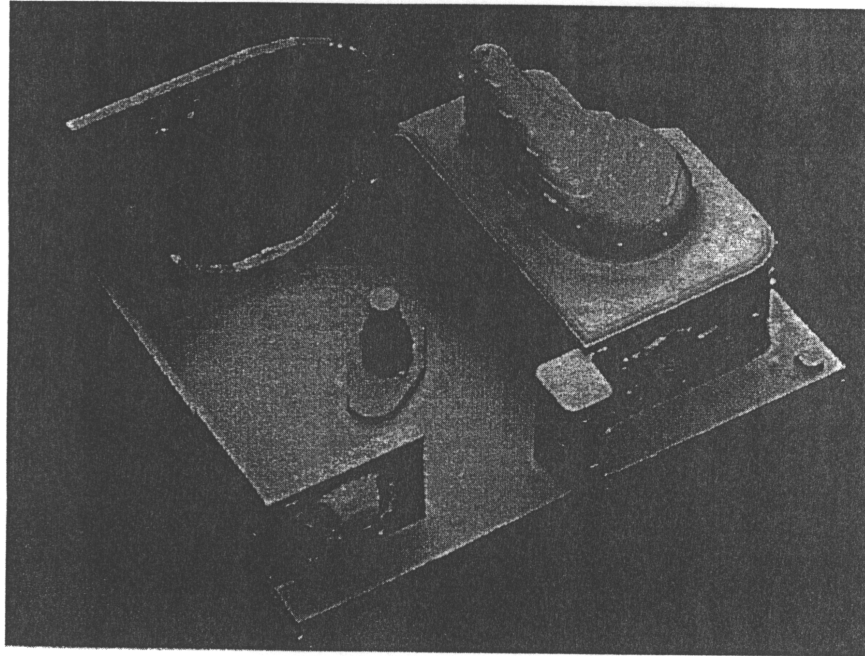


Figure 3.5.1.8 - IMS-T2

Data from mechanical testing of this material combination on individual tensile test specimens is shown in Table 3.5.1.1. The tensile strength for 308 weldments is specified at 597.2 MPa (86.6 ksi), the yield point at 399.9 MPa (58.0 ksi) and the elongation at 35%. The average tensile strength of microcast 308 is thus 17% higher, the yield point is 20% higher, and the elongation is 28% higher. While layer to layer bonding strength has not been tested yet, metallographic evidence suggests metallurgical bonding between the layers.

	tensile strength		0.2% offset yield		elongation
	[Mpa]	([ksi])	[Mpa]	([ksi])	[%]
min.	663.2	(96.2)	406.9	(59.0)	34.1
avg.	677.2	(98.2)	481.1	(69.8)	44.8
max.	685.7	(99.5)	499.5	(72.4)	58.4

Table 3.5.1.1 - Tensile test results for 308 stainless steel

## Conclusions

The implementation of a testbed facility and the creation of several test parts have demonstrated the potential of the Shape Deposition process as a future rapid manufacturing system for creating functional shapes. However, several issues must be addressed. In the current microcasting setup there is no direct control of the temperature of the underlying substrate and of droplet temperature, size and trajectories. This results in several problems leading to the existence of voids in the

deposited material and unwanted remelting effects. To reliably create high quality deposits a closed loop control system has to be developed, The issues involving residual stress buildup during deposition have to be identified, and the influence of shot-peening needs to be explored. Also, while evidence of good metallurgical bonding has been found between the individual layers, further investigations are necessary.

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This is a subset of a paper submitted to the Solid Freeform Fabrication Symposium, The University of Texas at Austin, August 8-10, 1994.

### **3.5.2. PANEL PRESENTATION BY JOSEPH J. BEAMAN, JR.**

**Desktop Manufacturing<sup>11</sup>**  
**Joseph J. Beaman, Jr.**  
**University of Texas at Austin**

#### **Abstract:**

Laser sintering process creates a solid, three-dimensional object using digital information transmitted by telephone to a selective laser sintering fabrication system.

Sitting at a desk, a designer has just created a computer rendition of an exotic shape for an equally exotic application or artistic expression. It is now time to create the actual object. Clicking on hard copy, the object materializes minutes later beside the desk. Is this the manufacturing environment of the future?

This dream represents an ideal method for manufacturing. In this approach, a part, component, or total subsystem would be designed electronically, taking advantage of the present power of computer-aided design systems. In a perfect world, the part, once designed, would be immediately produced with a push of a button. This seemingly fanciful manufacturing method is reminiscent of a more familiar concept, "desktop printing," where print and graphics are designed on a computer and then automatically printed by dot matrix, ink jet, or laser printers.

Let us consider at this time that printing is a good two-dimensional analogy to three-dimensional manufacturing. Lettering or drawing by hand is analogous to low volume manual manufacturing methods using standard machines and tools. Offset printing is analogous to high volume automated manufacturing using specialized machines. One method of printing that does not have an analogy in present manufacturing is desktop printing. Desktop printing does not compete with offset printing for large numbers of copies, but it is quite practical for small numbers.

This analogy illustrates an area of manufacturing research that has been conducted for several years under the guidance of Dr. Joel Barlow in Chemical Engineering, Drs. Harris Marcus and David Bourell in Material Science, and Dr. Richard Crawford and myself in Mechanical Engineering at The University of Texas at Austin. With the help of funding from the National Science Foundation and the Texas Advanced Technology Program, we have worked on new manufacturing technologies that produce freeform solid objects directly from a CAD database without part-specific tooling or human intervention. These technologies we have termed "Solid Freeform Fabrication," (SFF) or desktop manufacturing.

One of our most successful desktop manufacturing approaches is selective laser sintering. In this approach, components are built by material addition, rather than by material removal. In selective laser sintering, a directed laser beam is used to consolidate individual powder particles in selected regions. Compared to manual manufacturing methods, selective laser sintering is inherently fast. In addition, this process has the potential to produce accurate, structurally sound three-dimensional renditions of objects designed in a computer and to make such objects available to the user in minutes or hours.

The benefits of this new process include greatly reduced prototyping cost and design time, and the capability to achieve, in one operation, shapes that would otherwise require multiple operations or in some cases shapes impossible to manufacture with standard techniques. Conventional automated manufacturing technologies are well suited to large production numbers, but they are ill suited to the

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<sup>11</sup>Adapted from article in Discovery, Vol. 13, No. 1, pp. 18-22, 1993, Univ of Texas at Austin.



manufacture of low-volume production runs. This is due to a need to amortize the cost of part specific tooling over a large number of components. As a result, low production components are typically manufactured by manual methods that result in substantially higher unit costs and completion times. Even with the use of numerically controlled (NC) machining centers (computer controlled material removal systems) interfaced to CAD systems, the degree of human intervention commonly required to produce NC programs, set up NC machines, and supervise these machines while they run prevents these systems from being completely desirable options for low-volume production. It is in the low-volume production arena that desktop manufacturing offers a significant reduced cost and time to completion.

This new manufacturing technology will fit well into a computer integrated manufacturing environment. Desktop manufacturing has the capacity to dramatically shorten development cycles for complex systems by breaking the model making or prototyping bottleneck. Since part geometric (shape) information can be captured digitally in a CAD data base, this same information can be transmitted over telephone lines, radio signals, and via satellite.

Coupling this information with a selective laser sintering machine may provide the ability to get production on demand in remote locations or enable the local production of replacement parts and thus eliminate the need for large inventories. A long-term possibility is part production in space. Further coupling this technology with modern three-dimensional digitizing techniques, in which existing parts can be scanned with lasers or X-rays to capture their geometric information, provides the means to create three-dimensional copy or fax machines.

A three-dimensional fax was accomplished for the first time in August 1991 when a part was digitized at Scientific Measurement Systems, an Austin-based technology company that manufactures high-power X-ray scanning systems. This data was then sent over telephone lines to the Solid Freeform Fabrication Laboratory on the The University of Texas campus where a selective laser sintering system (see Figure 3.5.2.1) was used to re-create the part.

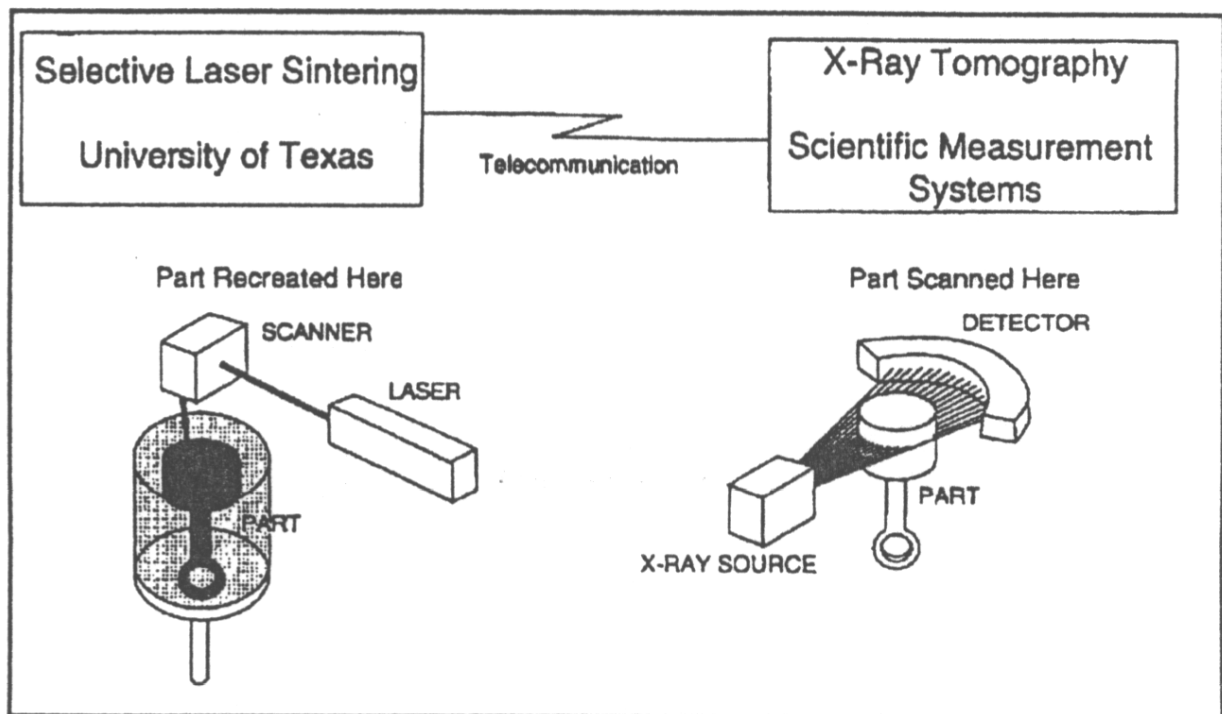


Figure 3.5.2.1 - Schematic of 3-D FAX Experiment

## Selective Laser Sintering.

This process begins by first depositing a thin layer of powder into a container. The powder surface is scanned with a high power energy beam such as a laser or electron beam. Beam intensity is modulated to locally sinter (fuse) the powder in areas to be occupied by the part at a particular cross-section. In areas not locally sintered, the powder remains loose and may be removed once the part is completed. Successive layers of powder are then deposited and sintered until the entire part is produced. Each layer is sintered deeply enough to join it to the underlying layer. Figure 3.5.2.2 illustrates the SLS process by which the parts were produced on a commercial version of our experimental hardware at the desktop manufacturing plant in Austin.

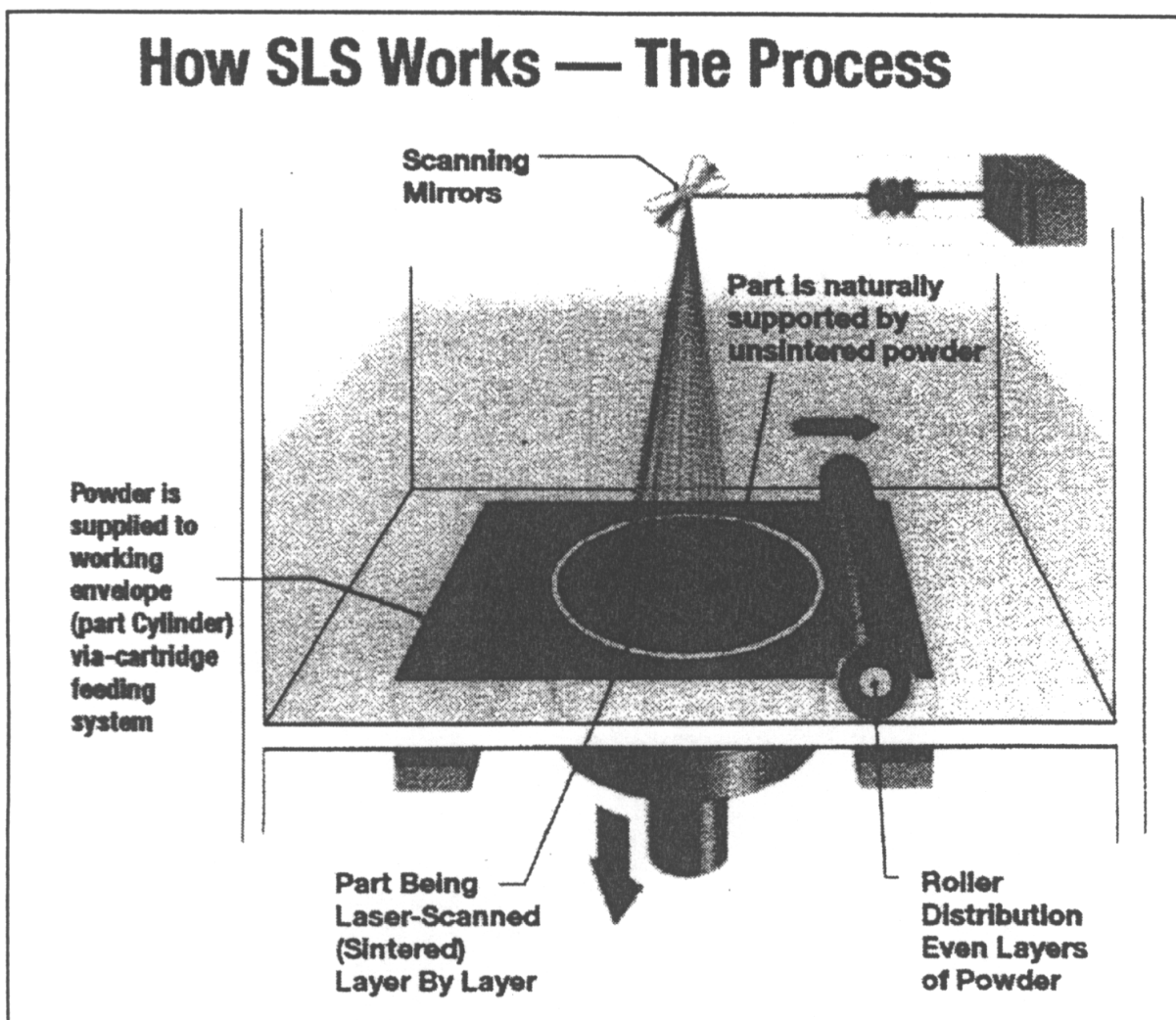


Figure 3.5.2.2 - Schematic of Selective Laser Sintering Process

The selective laser sintering process is regarded as a new technology with the greatest potential to dramatically alter the traditional methods of product design and manufacture. The multimaterial

nature of the process allows users to create functional and testable prototypes for developing and refining product designs across most manufacturing industries. Engineering thermoplastics used in the process include polycarbonate and nylon, with additional high performance materials under development. The laser sintering process can also produce complex patterns from standard casting wax used in the investment-casting industry.

Although investment casting is a manufacturing process that dates to the ancient Egyptians, who used a rudimentary version of the process to create such treasures as the bust of Pharaoh Tutankhamem, the process, in its modern form, is discovering an expanded use today. This process starts with a wax pattern that is dipped into a ceramic slurry. After the slurry is hard, the wax is melted and removed from the ceramic shell. The shell is then heated and metal is poured into the cavities. After a cooling cycle, the ceramic is removed to obtain the metal part. This process is used extensively in jewelry production, medical implants, and complex aerospace parts. One of the lengthiest portions of an investment casting process is the time to obtain a wax pattern. Traditionally, a metal mold must be fabricated in which wax is injected. The time to create these molds can be many months and many thousands of dollars. With the laser sintering process, wax pattern can be created directly within a day at a fraction of the cost of traditional methods.

## **Applications and Current Work.**

Major applications for the selective laser sintering process are found in the aerospace, automotive, computer, foundry, consumer goods, and medical industries. A common goal linking these manufacturing industries is the critical need to reduce the time and expense of getting new products to the marketplace. To achieve this end, many successful companies are seeking new technologies and processes to augment, and sometimes replace, traditional manufacturing processes such as prototyping and production tooling. Companies recognize that reducing total product development time and entering the marketplace ahead of the competition can mean the difference between market share leadership and a place among the many in a competitive market.

The medical industry has a great need for producing personalized parts in a rapid manner. Our joint research project with The University of Texas Health Science Center in San Antonio is investigating the possibility of automatically fabricating prostheses for below-the-knee amputees. Combining a laser digitizing system developed at the Health Science Center and the selective laser sintering process, we have been able to create prosthetic shapes in a fraction of the normal time. We are now evaluating the initial prosthetics on patients.

Aside from reducing the time-to-market, manufacturers are exploring the means to ensure product quality and cost reductions in manufacturing processes. Traditional mechanisms for prototype and production tooling often are too costly and time consuming, requiring a number of iterations and little flexibility for dynamic design changes that might improve the quality and costs of the final product. The selective laser sintering process is anticipated to significantly affect a manufacturer's ability to review and refine product designs quickly, avoid or expedite the tooling costs in the production process, and in some applications, generate low-volume production runs.

Future development of selective laser sintering capabilities for sintering of ceramic and metal materials is under way within the High Temperature Workstation Program at The University of Texas. The commercialization of devices using these materials in the selective laser sintering process will then affect industry through directly producing molds, tooling, dies, and fixtures in complex geometries and in materials matched closely to production process used by the manufacturer. The laser sintering process has the potential to make notable changes in the way future products are designed and manufactured across a variety of industries.